US Army Corps of Engineers

AQUATIC PLANT CONTROL
RESEARCH PROGRAM

MISCELLANEOUS PAPER A-91-3

PROCEEDINGS, 25TH ANNUAL MEETING, AQUATIC PLANT CONTROL RESEARCH PROGRAM

26-30 NOVEMBER 1990
ORLANDO, FLORIDA

June 1991

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Published by Environmental Laboratory
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1991

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Proceedings, 25th Annual Meeting, Aquatic Plant Control Research Program, 26-30 November 1990, Orlando, Florida

5. FUNDING NUMBERS

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Miscellaneous Paper A-91-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers, Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The 25th Annual Meeting of the US Army Corps of Engineers Aquatic Plant Control Research Program was held in Orlando, FL, on 26-30 November 1990, to review current research activities and to afford an opportunity for presentation of operational needs. Papers presented at the meeting are included in this report.

14. SUBJECT TERMS
Aquatic plant control—Congresses
Research planning—Congresses

15. NUMBER OF PAGES
313

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

Contents

Preface

The 25th Annual Meeting of the US Army Corps of Engineers Aquatic Plant Control Research Program (APCRP) was held in Orlando, FL, on 26-30 November 1990. The meeting is required by Engineer Regulation 1130-2-412, paragraph 4c, and was organized by personnel of the APCRP, which is managed under the Environmental Resources Research and Assistance Programs (ERRAP) of the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

The organizational activities were carried out and presentations by WES personnel were prepared under the general supervision of Mr. J. L. Decell, Program Manager, ERRAP, EL. Mr. Robert C. Gunkel, Assistant Program Manager, ERRAP, was responsible for planning the meeting. Dr. John Harrison was Chief, EL, WES. Mr. James W. Wolcott was Technical Monitor for the Headquarters, US Army Corps of Engineers.

Ms. Billie F. Skinner, Program Management Office, EL, was responsible for coordinating the necessary activities leading to publication. The report was edited by Ms. Jessica S. Ruff of the Information Technology Laboratory (ITL), WES. Ms. Betty Watson, ITL, designed and composed the layout.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

Agenda

Monday, 26 November 1990

1:00 p.m. -5:00 p.m.	***Registration*** (Floral Foyer)
3:00 p.m. -5:00 p.m.	***Federal Aquatic Plant Management Working Group*** (Tangerine Room A)
6:30 p.m. -8:00 p.m.	***Reception*** (West Pool Area)

Tuesday, 27 November 1990

8:00 a.m. -12:00 noon	***Registration*** (Floral Foyer)
8:30 a.m. -1:30 p.m.	***General Session*** (Jasmine & Magnolia Rooms)
8:30 a.m.	Call to Order and Announcements * R C. Gunkel, Assistant Manager, Aquatic Plant Control Research Program (APCRP) Waterways Experiment Station (WES) Vicksburg, Mississippi
8:40 a.m.	LTC J. D. Katin * USAE District Jacksonville, Florida
8:50 a.m.	D. E. Lewis * Chief, Natural Resources Management Branch Office, Chief of Engineers (HQUSACE) Washington, DC
9:05 a.m.	R W. Whalin * Technical Director, WES
9:15 a.m.	J. Harrison * Chief, Environmental Laboratory, WES

9:25 a.m.	Technical Monitor 1975-1980 * H. R. Hamilton, WES
9:40 a.m.	Technical Monitor 1980-1982 * D. L. Quarles, USAE District Fort Worth, Texas
9:55 a.m.	***Break***
10:30 a.m.	Technical Monitor 1983-1989 * E. C. Brown, WES
10:45 a.m.	Technical Monitor 19?0-? * J. W. Wolcott, HQUSACE
11:00 a.m.	J. L. Decell * Manager, Environmental Resources Research and Assistance Programs, WES
11:30 a.m.	Aquatic Plant Control Operations Support Center (APCOSC) Update * W. C. Zattau, USAE District Jacksonville, Florida
11:45 a.m.	Lewisville Aquatic Ecosystem Research Facility Update (32733) * R. M. Smart, WES
12:00 noon	***Lunch***
1:00 p.m.	Valuation of Aquatic Plant Economic Bene[illegible]s (32729) * J. E. Henderson, WES
1:15 p.m.	Video Imaging Project for Aquatic Plant Mapping (32732) * W. T. Jipsen, USAE District Jacksonville, Florida
1:30 p.m.	***Adjourn General Session***
8:30 a.m. - 5:00 p.m.	***Poster and Demonstration Session*** (Hibiscus & Azalea Rooms)
2:00 p.m. - 5:00 p.m.	***USAE Division/District Working Session*** (Lemon Room)

Wednesday, 28 November 1990

8:30 a.m. - 4:45 p.m.	***General Session*** (Jasmine & Magnolia Rooms)

Ecological Technology

J. W. Barko, WES, Presiding

8:30 a.m.	History and Overview of Major Advances in Aquatic Macrophyte Ecology * J. W. Barko, WES

8:45 a.m.	Population Dynamics of Submersed Macrophytes in the Tidal Potomac River (32351) * V. P. Carter, U. S. Geological Survey (USGS) Reston, Virginia
9:00 a.m.	Aquatic Macrophyte Competition Studies (32577) R. M. Smart, WES
9:15 a.m.	Habitat Value of Aquatic Macrophytes: Fisheries Considerations (32505) * K. J. Killgore, WES
9:30 a.m.	Habitat Value of Aquatic Macrophytes: Invertebrate Considerations (32505) * A. C. Miller, WES
9:45 a.m.	Littoral-Pelagic Nutrient Dynamics During Nighttime Convective Circulation (32405) * W. F. James, WES
10:00 a.m.	***Break***

Forum on the Future

10:30 a.m.	Sediment Interactions with Macrophytes / Growth and Distribution * J. W. Barko, WES
10:45 a.m.	Invertebrate Interactions with Macrophytes / Growth and Distribution * A. C. Miller, WES
11:00 a.m.	Ecological Perspectives in Aquatic Plant Management * C. S. Smith, WES
11:15 a.m.	Open Discussion
12:00 noon	***Lunch***

Biological Technology

A. F. Cofrancesco, WES, Presiding

1:00 p.m.	History and Overview * A. F. Cofrancesco, WES
1:15 p.m.	Management of Hydrilla and Eurasian Watermilfoil Using Insects (31799, 32730, 32734, 32735) * T. D. Center, U. S. Department of Agriculture (USDA) Fort Lauderdale, Florida
1:30 p.m.	Management of Eurasian Watermilfoil and Hydrilla Using Pathogens (32202, 32200) * C. S. Smith, WES
1:45 p.m.	Biotechnical Approaches to Aquatic Plant Management (32408, 32388) * S. L. Kees, WES
2:00 p.m.	Management of *Pistia* Using Insects (32406) * M. J. Grodowitz, WES

2:15 p.m.	Management of Hydrilla and Eurasian Watermilfoil Using Insects and Pathogens in Large Reservoir Systems (32734, 32735) * A. F. Cofrancesco, WES
2:30 p.m.	Management of Aquatic Vegetation Using Triploid Grass Carp in Large Reservoir Systems (32738) * L. G. Sanders, WES
2:45 p.m.	***Break***

Forum on the Future

3.15 p.m.	Overseas Biocontrol Research * J. K. Balciunas, USDA Fort Lauderdale, Florida
3:30 p.m.	Quarantine Operations and New Introductions * G. R. Buckingham, USDA Gainesville, Florida
3:45 p.m.	The Future of Microbial Herbicide * J. P. Stack, EcoScience, Inc. Amherst, Massachusetts
4:00 p.m.	Open Discussion
4:45 p.m.	***Adjourn General Session***
8:30 a.m. - 5:00 p.m.	***Poster and Demonstration Session*** (Hibiscus & Azalea Rooms)

Thursday, 29 November 1990

8:30 a.m. - 5:00 p.m.	***General Session*** (Jasmine & Magnolia Rooms)

Chemical Technology

K. D. Getsinger, WES, Presiding

8:30 a.m.	History and Overview * K. D. Getsinger, WES
8:50 a.m.	Herbicide Concentration/Exposure Time Relationships (32352) and Herbicide Delivery Systems (32437) * M. D. Netherland, WES
9:10 a.m.	Submersed Application Techniques for Flowing Water (32354) and Field Evaluation of Selected Herbicides (32404) * K. D. Getsinger, WES
9:30 a.m.	Plant Growth Regulators for Aquatic Plant Management (32578) * L. S. Nelson, WES

9:50 a.m.	Phenology of Aquatic Plants (32441) * J. D. Madsen, WES
10:00 a.m.	***Break***

Forum on the Future

10:30 a.m.	Industry Forecast * F. T. Lichtner, E. I. Du Pont Discovery Group Newark, Delaware
10:45 a.m.	Operational Perspective * J. C. Joyce, Center for Aquatic Plants, University of Florida Gainesville, Florida
11:00 a.m.	Regulatory Issues * J. H. Rodgers, University of Mississippi Oxford, Mississippi
11:15 a.m.	Open Discussion
12:00 noon	***Lunch***

Simulation Technology

R. M. Stewart, WES, Presiding

1:00 p.m.	Historical Perspective and Overview * R. M. Stewart, WES
1:30 p.m.	Plant Growth Simulations (32440) * J. W. Wooten, University of Southern Mississippi Hattiesburg, Mississippi
1:50 p.m.	Biocontrol Simulations (32438) * W. A. Boyd and R. M. Stewart, WES
2:10 p.m.	Chemical Control Simulations (32439) * J. H. Rodgers, Jr., University of Mississippi Oxford, Mississippi
2:30 p.m.	Aq[illegible]c Plant Data Bases: Lake Marion (32506) * R. A. Welch and M. M. Remillard, University of Georgia Athens, Georgia
2:45 p.m.	***Break***

Forum on the Future

3:15 p.m.	Simulation Needs for the Future * R. M. Stewart and H. W. West, WES

3:45 p.m.	Open Discussion
4:30 p.m.	Report on Tuesday's Division/District Working Session
5:00 p.m.	***Adjourn 25th Annual Meeting***

Friday, 30 November 1990

8:30 a.m. - 11:00 a.m.	FY92 Civil Works R&D Program Review (Corps of Engineers Representatives Only) (Jasmine Room)

Posters and Demonstrations

Poster Presentations

Tuber Production and Germination Studies (32351)
* D. G. McFarland, WES

Benthic Barrier Environmental Studies (32579)
* H. L. Eakin, WES

Benthic Barrier Invertebrate Studies (32579)
* B. S. Payne, WES

Simulation Modeling and Spatial Data Bases (32506)
* M. R. Kress, WES

New Biocontrol Agents
* W. C. Durden, USDA, Fort Lauderdale, and J. E. Freedman, WES

Computer Demonstrations

Simulation Models
* R. M. Stewart, WES
  HYDRILLA & MILFOIL (Tuesday, 27 November, 8:30 a.m. - 12:00 noon)
  INSECT & HERBICIDE (Tuesday, 27 November, 1:00 p.m. - 5:00 p.m.)
  AMUR/STOCK & HARVEST (Wednesday, 28 November, 8:30 a.m. - 12:00 noon)

Expert System
* M. J. Grodowitz, WES

Aquatic Plant Imaging Project (32732)
* W. T. Jipsen, USAE District
  Jacksonville, Florida

Attendees

John Adams
USAE District, Jacksonville
P.O. Box 4970
Jacksonville, FL 32232-0019

Les Ager
Georgia Dept. Natural Resources
Rt. 3, Box 75
Fort Valley, GA 31030

Nancy Allen
USAE District, Jacksonville
P.O. Box 188
Inglis, FL 32675

Lars Anderson
USDA/ARS
Aquatic Weed Research
University of California
Davis, CA 95616

Bob Bailey
USAE Division, Lower Mississippi Valley
P.O. Box 80
Vicksburg, MS 39180-0080

Gordon Baker
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680

Joe Balciunas
USDA/ARS
Australian Biological Control Lab
Townsville, Australia

Eric Barkemeyer
Atochem North America
7506 E Independence Blvd.
Charlotte, NC 28227

John Barko
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Jim Barrows
USAE District, Galveston
P.O. Box 1229
Galveston, TX 77553-1229

Leon Bates
Tennessee Valley Authority
Aquatic Biology Dept., OSA 1S 122B
Muscle Shoals, AL 35660

Matt Beaver
Natural Resources Office
525 Ridgelawn Road
Clewiston, FL 33440

Chris Bennett
University of Florida
Biological Control Laboratory
Gainesville, FL 32611

Nancy Bloodwell
Orange County/Orlando Convention Bureau
Orlando, FL 32802

Mike Bodle
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680

William Boyd
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Carl Brown
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Gary Buckingham
USDA/ARS
P.O. Box 1269
Gainesville, FL 32602

Dave Buelow
US Army Corps of Engineers
20 Massachusetts Ave., NW
Washington, DC 20314-1000

Earl Burns
Tennessee Valley Authority
OSA 1S 122B
Muscle Shoals, AL 35660

Virginia Carter
US Geological Survey
430 National Center
Reston, VA 22092

Ted Center
USDA/ARS
3205 College Ave.
Fort Lauderdale, FL 33314

George Chambers
Tennessee Valley Authority
OSA 1S 122B
Muscle Shoals, AL 35660

Philip Chiocchio
University of Florida
Center for Aquatic Plants
7922 NW 71st St.
Gainesville, FL 32606

Cesar Von Chong
Panama Canal Commission
APO Miami, FL 34011-5000

Phil Clifford
EA Engineering Science & Technology
15 Loveton Circle
Sparks, MD 21152

Al Cofrancesco
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Bob Corke
Dept. of Water Resources
State of California
4721 D St.
Sacramento, CA 95819

Ernest Corley
US Dept. of Agriculture
P.O. Box 5677
Athens, GA 30613

Robert Creed
Middlebury College
Middlebury, VT 05753

Joseph Debler
USAE District, New York
26 Federal Plaza
New York, NY 10278-0090

Lewis Decell
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Nate Dechoretz
California Dept. of Food and Agriculture
1220 N Street, Rm A357
Sacramento, CA 94271-0001

Steve deKozlowski
South Carolina Water Resources Co.
1201 Main St.. Suite 1100
Columbia, SC 29201

David DeMont
NCDEHNR-Water Resources
P.O. Box 27687
Raleigh, NC 27611

D. Deonick
Department of Zoology
Miami University
Oxford, OH 45056

Gary Dick
USAE Lewisville Aquatic Ecosystem
Research Facility
Rt. 3, Box 446
Lewisville, TX 75067-9720

Mark Dutton
USAE District, Savannah
P.O. Box 889
Savannah, GA 31402-0889

Harry Eakin
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Michael Eubanks
USAE District, Mobile
P.O. Box 2288
Mobile, AL 36628-0001

Jan Freedman
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Johnnie Frizzell
Atochem North America
Rt. 1, Box 471
Hope Hull, AL 36043

Anne Galloway
USAE District, Jacksonville
P.O. Box 4970
Jacksonville, FL 32232-0019

Sherman Gee
USAE Division, Ohio River
P.O. Box 1159
Cincinnati, OH 45201-1159

Kurt Getsinger
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Michael Grodowitz
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Bob Gunkel
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Haim Gunner
Department of Plant and Soil Science
Marshall Hall
University of Massachusetts
Amherst, MA 01003

Dale Habeck
University of Florida
Dept. of Entomology and Nematology
Gainesville, FL 32611

Kathy Hamel
Department of Ecology
Moduline Building, PV-11
Olympia, WA 98504

Roger Hamilton
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Jim Henderson
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Sue Hennig
Municipality of Metropolitan Seattle
821 Second
Seattle, WA 98104

Simeon Hook
USAE District, New York
26 Federal Plaza
New York, NY 10278-0090

John Jackman
Department of Entomology
411 Heep Center
College Station, TX 77840

William James
USAE Eau Galle Limnological Laboratory
Box 237
Spring Valley, WI 54767

Wayne Jipsen
USAE District, Jacksonville
ATTN: CESAJ-CO-OR
P.O. Box 4970
Jacksonville, FL 32232-0019

Joyce Johnson
Texas Parks and Wildlife
4200 Smith School Road
Austin, TX 78744

Steve Jones
Alabama Power Co.
P.O. Box 2641
Birmingham, AL 35291

Joe Joyce
University of Florida
Center for Aquatic Plants
7922 NW 71st St
Gainesville, FL 32606

LTC Jon Katin
USAE District, Jacksonville
P.O. Box 4970
Jacksonville, FL 32232-0019

Stewart Kees
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Joe Kight
USAE District, Mobile
Lake Seminole Resource Manager's Office
P.O. Box 96
Chattahoochee, FL 32324

Jack Killgore
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Rose Kress
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Howard Krosch
Minnesota Department of Natural Resources
500 Lafayette Road
St. Paul, MN 51555

Errigh Laboo
USAE District, Baltimore
P.O. Box 1715
Baltimore, MD 21203-1715

Carole Lembi
Purdue University
Dept. of Botany and Plant Pathology
West Lafayette, IN 47907

Darrell Lewis
US Army Corps of Engineers
20 Massachusetts Ave., NW
Washington, DC 20314-1000

Frank Lichtner
Du Pont Co., Inc.
Agricultural Products
Stine-Haskell Res. Center
P.O. Box 30
Newark, DE 19711

Dick Lillie
Wisconsin Department of Natural Resources
3911 Fish Hatchery Road
Fitchburg, WI 53711

Michael Link
Du Pont Co.
Rt. 4, Box 665
Byron, GA 31008

Michael Loesch
USAE Division, North Central
536 South Clark Street
Chicago, IL 60605-1592

Judy Ludlow
Florida DNR
Orlando, FL 32802

John Madsen
USAE Lewisville Aquatic Ecosystem
Research Facility
Rt. 3, Box 446
Lewisville, TX 75067-9720

Larry Mangum
Tennessee Valley Authority
OSA 1S 116B
Muscle Shoals, AL 35660

Shane McCarthy
NCDEHNR-Water Resources
P.O. Box 27687
Raleigh, NC 27611

Bobby McDuff
Tennessee Valley Authority
OSA 1S 122B
Muscle Shoals, AL 35660

Dwilette McFarland
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

M. McLeod
Griffin Corporation
P.O. Box 1847
Valdosta, GA 31603-1847

Terry McNabb
Aquatics Unlimited/Enviroscan
6821 S. 220th St.
Kent, WA 98032

Andrew Miller
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Allen Moore
Department of Ecology
State of Washington
Olympia, WA 98504

Bill Moore
Atochem North America
210 Valencia Shores Dr.
Winter Garden, FL 34787

Joe Morrison
USAE District, Nashville
P.O. Box 1070
Nashville, TN 37202-1070

Herb Nelson
USAE District, St. Paul
1421 USPO and Custom House
St. Paul, MN 55101-1479

Linda Nelson
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Mike Netherland
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Fred Nibling
US Bureau of Reclamation
P.O. Box 25007, D. 3742
Denver, CO 80225

Charles O'Brien
Entomology-Biocontrol
Florida A&M Univ.
Tallahassee, FL 32317

Pat O'Leary
EcoScience Laboratories
85 N Whitney
Amherst, MA 01002

Barry Payne
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Tom Pellett
1350 Femrite Dr.
Monona, WI 53716

John Peter
Du Pont Co.
Wilmington, DE 19880-0253

Chip Pierson
USAE District, Portland
P.O. Box 2946
Portland, OR 97201-2946

David Pott
Harza Engineering Co.
150 S Wacker Dr.
Chicago, IL 60606-4288

Jim Preacher
USAE District, Charleston
P.O. Box 919
Charleston, SC 29401-0919

Gerald Purvis
USAE Division, South Atlantic
77 Forsyth St. SW
Atlanta, GA 30335-6801

Dwight Quarles
USAE District, Fort Worth
P.O. Box 17300
Fort Worth, TX 76102-0300

P. Peloquin
USAE Division, North Pacific
P.O. Box 2870
Portland, OR 97208-2870

Vic Ramey
University of Florida
Center for Aquatic Plants
7922 NW 71st St.
Gainesville, FL 32606

Bob Rawson
USAE District, Seattle
P.O. Box 3755
Seattle, WA 98124-2255

Marguerite Remillard
CRMS, Department of Geography
University of Georgia
Athens, GA 30602

Michael Remington
Imperial Irrigation District
P.O. Box 937
Imperial, CA 92251

David Roberts
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

John Rodgers
Department of Biology
University of Mississippi
University, MS 38677

Bill Rushing
US Army Corps of Engineers
20 Massachusetts Ave., NW
Washington, DC 20314-1000

Gloria Rushing
9318 Willow Creek Dr.
Apt. H
Gaithersburg, MD 20879

Larry Sanders
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Jeff Schardt
Florida Department Natural Resources
2051 E Dirac Dr.
Tallahassee, FL 32310

Sallie Sheldon
Middlebury College
Middlebury, VT 05753

Maurice Simpson
USAE District, Nashville
P.O. Box 1070
Nashville, TN 37202-1070

Billie Skinner
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Michael Smart
USAE Lewisville Aquatic Ecosystem
Research Facility
Rt. 3, Box 446
Lewisville, TX 75067-9720

Carl Smith
USAE District, Wilmington
P.O. Box 1890
Wilmington, NC 28402-1890

Craig Smith
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Edward Snoddy
Tennessee Valley Authority
OSA 1S 122B
Muscle Shoals, AL 35660

Jim Stack
EcoScience Laboratories
85 N Whitney
Amherst, MA 01002

Brad Stannard
MSE
4044 Sunset Dr.
Spring Park, MN 55384

Joe Stephenson
Alabama Power Co.
P.O. Box 2641
Birmingham, AL 35291

Kerry Steward
USDA/ARS
3205 College Ave.
Fort Lauderdale, FL 33314

Mike Stewart
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Chuck Swanman
Applied Biochemists
415 Bamboo Lane
Largo, FL 34640

Tom Swor
USAE District, Nashville
P.O. Box 1070
Nashville, TN 37202-1070

David Tarver
DowElanco
Tallahassee, FL 32301

Dan Thayer
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680

Ed Theriot
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Glenn Turner
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Thai Van
USDA/ARS
3205 College Ave.
Fort Lauderdale, FL 33314

David Webb
Tennessee Valley Authority
OSA 1S 122B
Muscle Shoals, AL 35660

Ted Werner
USAE District, Sacramento
650 Capital Mall
Sacramento, CA 95814-4794

Wade West
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Howard Westerdahl
Battelle Pacific NW Laboratory
P.O. Box 999, MSIW K6-05
Richland, WA 96352

Robert Whalin
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Susan Whittington
USAE Division, South Atlantic
77 Forsyth St., SW
Atlanta, GA 30335-6801

Linda Winfield
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Jim Wolcott
US Army Corps of Engineers
20 Massachusetts Ave., NW
Washington, DC 20314-1000

Jean Wooten
University of Southern Mississippi
Box 5018
Hattiesburg, MS 39406

Lois Wright
Orange County/Orlando Convention Bureau
Orlando, FL 32802

Bill Zattau
USAE District, Jacksonville
P.O. Box 4970
Jacksonville, FL 32232-0019

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
gallons (US liquid) per acre	0.00093	cubic decimeters per square meter
inches	2.54	centimeters
miles (US statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
pounds (mass) per acre	0.000112	kilograms per square meter
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square miles	2.589998	square kilometers
tons (mass) per acre	0.22	kilograms per square meter
tons (2,000 pounds, mass)	907.1847	kilograms

25th Annual Meeting US Army Corps of Engineers

AQUATIC PLANT CONTROL RESEARCH PROGRAM

Introduction

The Corps of Engineers (CE) Aquatic Plant Control Research Program (APCRP) requires that a meeting be held each year to provide for professional presentation of current research projects and to review current operations activities and problems. Subsequent to these presentations, the Civil Works Research and Development Program Review is held. This program review is attended by representatives of the Civil Works and Research Development Directorates of the Headquarters, US Army Corps of Engineers; the Program Manager, Environmental Resources Research and Assistance Programs (ERRAP); and representatives of the operations elements of various CE Division and District Offices.

The overall objective of this annual meeting is to thoroughly review the Corps aquatic plant control needs and establish priorities for future research, such that identified needs are satisfied in a timely manner.

The technical findings of each research effort conducted under the APCRP are reported to the Manager, ERRAP, US Army Engineer Waterways Experiment Station, each year in the form of periodic progress reports and a final technical report. Each technical report is distributed widely in order to transfer technology to the technical community. Technology transfer to the field operations elements is effected through the conduct of demonstration projects in various District Office problem areas and through publication of Instruction Reports, Engineer Circulars, and Engineer Manuals. Periodically, results are presented through publication of an APCRP Information Exchange Bulletin which is distributed to both the field units and the general community. Public-oriented brochures, movies, and speaking engagements are used to keep the general public informed.

The printed proceedings of the annual meetings are intended to provide all levels of Corps management with an annual summary to ensure that the research is being focused on the current nationwide operational needs.

The contents of this report include the presentations of the 25th Annual Meeting held in Orlando, FL, on 26-30 November 1990.

Welcoming Remarks

by
LTC J. D. Katin[1]

Let me welcome you all to the Silver Anniversary meeting of the Aquatic Plant Control Research Program. It's most appropriate that the Jacksonville District was chosen as the location for this meeting, as Florida has always been one of the busiest places for APC activities.

The foundation for today's APC Program was laid during the last century when heinous weeds clogged Florida's waterways. Your forbearers grappled with waterhyacinth in the beautiful and busy St. Johns River in the 1890's. Joint efforts by the State's citizens and legislators, along with the Corps, brought about language in the 1899 Rivers and Harbor Act to deal with waterhyacinth and other nuisance aquatic plants.

The modern Aquatic Plant Control Program was authorized in 1965, and today we work together with local, state, and other national agencies to combat plants that impede navigation, interfere with recreation activities, and adversely affect water quality.

Legislation comes and goes, but it seems our problems with aquatic plants will always be with us, at least at some level. The good news is that, with mechanical, biological, chemical, and environmental manipulation techniques, we are winning the battle. Research in herbicide use for aquatic plant control in flowing-water situations has enjoyed enormous success, especially in the Withlacoochee River, which you visited yesterday.

I would like to emphasize the importance of biological methods to fight nuisance aquatic plants because, as most of you know, the Corps of Engineers is moving into the forefront of working to protect and preserve the environment while we accomplish our many missions.

The APC Program is a leader in this mandate. As you forge ahead in researching new techniques for managing aquatic plants, a new foundation is laid for environmentally sound solutions to man's challenges in the 21st century.

Due in part to chemical and biological methods, waterhyacinth in Florida is at its lowest level this century. The waterlettuce weevil is doing a splendid job, as is the alligatorweed flea beetle.

Throughout the years, my District has funded important research involving mechanical, chemical, and biological control technology. We are convinced that these investments have paid for themselves many times over. The Aquatic Plant Control Operations Support Center is now entering its second decade of service. The Center responded to more than 140 contacts last fiscal year, and expects another busy year.

Along with our partnership with the environment, we enjoy a wonderful partnership with many local, state, and national entities that work in concert with us in managing nuisance aquatic plants. This relationship is crucial to the success of the program, and I'm confident it will continue to grow and flourish like untreated hydrilla.

I wish you all a productive and stimulating meeting.

---

[1] Deputy District Engineer, US Army Engineer District, Jacksonville; Jacksonville, FL.

A Perspective of Significant Events in the Aquatic Plant Control Program 1975-1980

H. Roger Hamilton[1]

The Aquatic Plant Control Program has been in existence for well over a quarter of a century. Authority for the program is contained in Section 104 of the River and Harbor Act, approved 3 July 1958, as amended. The first recorded annual meeting on this topic occurred in Athens, Georgia, on 27 October 1965. That was 10 years before I was appointed as Technical Monitor for the program.

Since my term as Technical Monitor for this program is the first one to be addressed today, permit me to set the stage by telling you what I know of the first decade of the program, how I became involved in it, and some history of what drove some of the early decisions that charted the course of the Aquatic Plant Control Program in the Corps of Engineers and led to work under way today.

Since the passage of the authorizing legislation in 1958, the efforts of the Corps of Engineers in controlling aquatic plant populations had been rather localized in nature. The thrust of the operational work had been limited to clearing and maintaining important navigation channels in the southeastern United States. Research consisted of arrangements with the US Department of Agriculture and a few universities to identify insect control agents and the development of a laser-powered device to destroy plants.

Major General John W. Morris was Director of Civil Works in the Office of the Chief of Engineers. He was not satisfied with progress on three elements of his mission: (1) Master Plan development and review, (2) review of Environmental Impact Statements for operating projects, and (3) the Aquatic Plant Control Program. In 1975, he transferred responsibility for these programs to the Recreation-Resources Management Branch (now the Natural Resources Management Branch) in the Construction-Operations Division (now the Operations, Construction, and Readiness Division) of the Civil Works Directorate. As Chief of the Natural Resources Management Section, I inherited all three programs.

These additional duties were added onto an already full schedule, a typical situation. My plan was to ease into these new responsibilities as I was able to learn something of the current status of each and develop my goals of future expectations. Two weeks later I found new motivation to accelerate that process when General Morris summoned me to his office to present a status report on my progress in each of the programs. Clearly, I had been presented with the opportunity to succeed or fail—another typical situation. I immediately decided to succeed.

It did not take long to discover that much work lay ahead to properly define the scope of the aquatic plant problem and formulate a strategy to elevate the visibility of the problem and set in motion a plan of action. The first obvious item on the agenda was to determine the status of the program. Contact with key District representatives was initiated. I also called for a meeting with representatives from the Waterways Experiment Station (WES).

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

After a series of meetings on the subject, I confirmed several facts about the program.

- Operations had been confined to specific problem areas in the southeastern United States. Accordingly, any visibility for the program was regional in nature.

- Operational efforts were primarily directed toward maintenance spraying of navigation channels and selected problem areas. Resources were not adequate to make additional progress and, in years of good plant growth, maintenance of the high-impact areas was not complete. Thus, the regional visibility that we had was not always favorable.

- Research had been modest in scope. The laser control device had been developed, but had not proven successful. It was too large and cumbersome to maneuver into water areas where the problem plants thrive. Some work was under way to register herbicides, and some limited work had been done on biological agents. Mechanical harvesters of assorted descriptions, with ranging capabilities and varying price tags, were in various stages of development and testing.

- Annual meetings were held beginning in 1965, but attendance was limited to the few operations and research personnel who were working on specific problems in the Southeast. Professional interaction between the researchers and the practitioners was limited.

- Authority for planning and management activities of the program was organizationally diverse among the Districts and Divisions. One might find this responsibility vested in an Operations, Planning, or Engineering Division depending on which District or Division office one visited. This situation was both good and bad. Communications in the "stove-piped" structure of the Corps of Engineers were difficult. On the positive side, an excellent opportunity for cross-fertilization of ideas and talents across organizational lines was presented.

- Authorization authority for appropriations was limited to $5 million annually. Actual appropriations fell well below that authorization level, and the available funds were directed almost exclusively to maintenance activities, primarily herbicide spraying in Florida and Louisiana.

Based on this information and General Morris' instructions to "give the program national recognition without becoming a national problem," I set upon a course to reorder the implementation of the Aquatic Plant Control Program.

Most of the limited funds were devoted to maintenance spraying by in-house spray crews and by contract. Little was spent on research, and the coordination between research efforts and operations needs was not always obvious.

I made a conscious effort to divert more funding to the research and development activities. This was often at the dismay of District personnel who initially had to suffer some slight budget cuts. However, funding levels were quickly elevated to accommodate maintenance work and enhance the research level. I was convinced that long-term solutions to a problem of this magnitude could only come from a well-orchestrated research and development program designed to provide a better understanding of the problem situation and explore all potential solutions.

Conversations with representatives of the WES revealed that work had been under way, primarily by the US Fish and Wildlife Service, to develop the capability to produce a monosexual population of a rather controversial fish that was known to feed on aquatic plants. The white amur or grass carp

(*Ctenopharengodon idella*) was believed to be a viable biological control agent. However, it had not been tested because many biologists and sportsmen feared that release of the fish into American waters would result in the destruction of habitat for game and forage species, in much the same way the release of German carp had done several years earlier. Indeed, 22 states had laws forbidding the possession of this species.

The ability to produce a sterile population would facilitate such a test. Added safety precautions were present in the configuration and natural security of the test site. Lake Conway, located just outside Orlando, FL, was selected as the test site for a 5-year Large-Scale Operations Management Test.

Lake Conway was essentially a closed system, with outlets that were easily blocked to prevent fish escapes. It contained a large hydrilla population and was geographically located to optimize the visibility of the field test. We were gambling that the test would be successful in terms of producing answers, either positive or negative, regarding the utility of the grass carp as a biocontrol agent. The success would lie in the professional and scientific approach to the field test, more than in the answers that resulted.

This was the first such large-scale demonstration, and it was used effectively to test the efficacy of this biocontrol agent under conditions designed to prevent the release of the fish into American waters. It also served as an excellent vehicle to elevate and expand the visibility of the Aquatic Plant Control Program in positive terms and to build credibility, both inside and outside the agency, for our administration of the program.

The large-scale test was jointly sponsored by Jacksonville District and the WES. This arrangement worked quite satisfactorily and, although all of the players might not have realized it, set the stage for a similar field test for control of waterhyacinths in Louisiana, which was cooperatively managed by WES and the New Orleans District.

Other dynamics of organizational evolution were also at work. The establishment of the Aquatic Plant Control Operations Support Center in the Jacksonville District was a direct outgrowth. Planning for the Center began in my term and was implemented after my departure. Emphasis was placed on identification of personnel in field offices who possessed the educational background and experience, along with the desire to make the program successful. Efforts were then made to get these key people assigned to the program. They formed the nucleus of the professional staff to implement field planning and operations functions and to advise the research community of problems to be researched and the applicability of research results to field situations. Organizational lines are still crossed, but in a very positive manner with better products as a result. To some extent, I feel the Aquatic Plant Control Program has been a catalyst for positive change in this regard.

The annual meetings were formalized and structured to serve as a forum for interaction among researchers and practitioners; among Corps personnel and other Federal and non-Federal representatives, university personnel, and the private sector; among planners and managers; and among representatives of any sector that has an interest in managing populations of problem aquatic plants.

Guidance to Corps field offices was prepared and distributed in the form of ER 1130-2-412, Aquatic Plant Control Program. This Engineer Regulation described the program objectives and criteria and procedures for recommending work in the program. Additionally, the policy guidance established the requirement for an annual meeting to "provide for professional presentation of current research projects, review of current operation activities, and review of new research proposals." That is why we are meeting this week.

The attendance of District and Division personnel at the annual meeting was authorized by this policy guidance. This is a very important point that might go unnoticed by

one not familiar with the operation of government bureaucracies. Interaction among scientists and practitioners is essential to set and achieve common goals in this program. Travel funds and time away from the office for regional or national meetings are often difficult to obtain. Authorized participation through the medium of an Engineer Regulation, coupled with supplementary letters requesting District reports on the status of operations and needs from the research community, is very important to the assurance of participation and interaction by the right people. If we get a "disconnect" between the practitioner who has the problem and needs a solution and the scientist who has the skill to attack the problem and develop a solution, failure is often the result.

To implement my decision to "drop the losers and go with the winners" as a means of gaining credibility and positive visibility for the program, we examined all ongoing and potential work. In summary, the following major directional changes were made.

- The research on laser applications was terminated. Some important information had been gained, but there was no need to go further. The most important thing we had learned was that, in its configuration at that time, the machine was not effective for aquatic plant control.

- Several mechanical harvesters were developed and tested, mostly at the expense of the developer from the private sector. Some showed promise; several did not. Some major logistical problems were encountered. For example, transport of the harvested plant material from its growing site to a disposal site was time- and energy-consuming. Disposal of the material itself presented problems. Travel by the harvesters to and from and within areas that needed to be controlled was difficult or impossible. Harvesters generally lacked the ability to cover large areas of plant infestation as efficiently or as effectively as other control methods. Some proved successful for implementation in limited areas.

- Efforts were made to discover beneficial uses of harvested plants. If we could create a market for the plants, our problems would be solved. A low grade of paper was made. The plants were used as a soil supplement. They were incinerated to provide energy. Favorable results were minimal.

- Chemical applications were effective, but primarily as a maintenance measure. Registration by the Environmental Protection Agency limits the chemical formulations that can be used.

- Biological controls such as insects and fish seemed to present the most perplexing short-term problems, but also seemed to hold the most hope for long-term solutions.

- We thought about management strategies, such as water-level manipulation, that might be employed. Applications were found in some situations, but they were limited. We were too early in the development of the program to thoroughly think these concepts through.

- Efforts were started to elevate the funding appropriations and authorization levels.

During the review of past and ongoing work and the attempts at setting direction for the program, we were able initially to develop the Aquatic Plant Control Program into the subareas of chemical, mechanical, and biological. As the program developed, the terms environmental manipulation and integrated control evolved.

It was clear that a better understanding of the ecology and physiology of problem plants was essential to identification and

development of control agents. It took a few years (past my tenure) to begin that type of research. It was also apparent that total costs and benefits of the control of aquatic plants were unknown, and techniques had not yet been devised to perform such measurements. We have just recently begun this work.

During the process of getting the program up and running, much knowledge was gained about the problem plant populations and their impacts on water resources projects. However, it seemed that for each fact learned, about five questions emerged. The questions were increasing geometrically, and the answers were increasing only arithmetically—in fractions.

This has been a very quick overview of some of the highlights of the program during a 5-year period. In summary, even though the program had been authorized and in operation as much as 17 years before I became involved, a new direction was charted and implementation began during the period 1975 to 1980. National visibility was achieved. The program did not become a national problem, but problems of aquatic plant infestation were discovered in several locations throughout the Nation. A new direction for the program was set in motion toward some realistic and achievable goals. Those that followed me have been very successful in steering the program in a manner to improve management of problem aquatic plant populations in our Nation's waterways. To them go any credit for the success of this program to date.

It has been said that success is a journey, not a destination. It was my privilege to participate in a small portion of that journey.

Summary of Involvement as Technical Monitor of the Aquatic Plant Control Research Program 1980-1982

by
Dwight L. Quarles[1]

I was really thrilled to get the invitation to come to this meeting. I look forward to seeing all the people I got to know when I was involved with the program. Although excited about the invitation, I was sort of concerned as to just what someone who has been out of the program for eight years could tell a group such as this. My experience has been that after being out of the program for a while what I remember about it is sort of an assortment of somewhat surrealistic recollections of some events which occurred on my watch. I'll share some of them with you.

I'm sure you have all heard by now about the "dyslexic agnostic" who developed insomnia and laid awake at night pondering the question: "is there really a dog?" I must confess that I came in to the program as somewhat of a "dyslexic agnostic" (agnostic in that I wasn't sure if I believed in it, and dyslexic because it took me a long time to figure out how to look at it). I left a true believer. I think I learned a lot about the program itself and more broadly about the Corps and its overall management of resources to accomplish work.

I became involved in fiscal year 1981 after Roger Hamilton rode off to Fort Worth to work in the environmental planning area. Roger left me some phone numbers at WES. One day I finally called one of them, and a voice on the other end (later identified as Lewis Decell) said: "Send money."

When I started as tech monitor, the age of Aquarius was really in full swing. All you astrology buffs know that the zodiac sign aquarius signifies the water bearer or water carrier. When I became tech monitor, the age of water hauling (also known as mechanical harvesting program) was by far the largest part of the program. Because of the high water content of the plants harvested, we really did move a lot of water around in this program. We also learned a tremendous amount about the harvesting and disposal of problem aquatic plants.

In the mechanical program we had performed somewhat like a "vegamatic" in that we had:

sliced it	throttled it
diced it	trashed it
hauled it	mashed it
mauled it	thrased it
stowed it	skewed it
towed it	dreaded it
hedged it	bred it
dredged it	and
modeled it	chopped it

but by no means stopped it. And Lewis Decell said: "Send money."

So like Lucrecia Borgia and her family, we decided to resort to poison. This was known as the chemical control work units. Here we had Roundups and Rodeos, sprays, emulsions, inverts, and pellets. We applied by land, sea, and air. We used power boats and air boats. We used fixed-wing and rotary-wing aircraft. We treated lanes, areas, floating species, and submersed species. We obtained temporary registrations for at least one herbicide. (All I can say about the

[1] US Army Engineer District, Fort Worth; Fort Worth, TX.

temporary registration process is, don't get into it unless you are interested in self-flagellation.)

We just drove those little growth hormones crazy, and those little hormones continued to prompt growth. And Lewis Decell said: "Send money."

So we decided to feed the fish and the flea beetles and other organisms. This effort was called the biological control work units. We tried the white amur, moths, beetles, and fungi. And we probably tried critters I've long since forgotten. We participated in the US Patent process. We enjoyed our share of success and failures.

We learned that biological techniques can be political lightning rods, "Bass fishermen just love hydrilla and they sure don't trust any weed-eating fish or the people proposing to use such critters." But the spread went on, and Lewis Decell said: "Send money."

At about this point someone asked "what the heck makes these critters grow anyway" or, more importantly, just what would limit their growth? So we looked at physical requirements, biological needs, synergistic phenomena, man's contributions (fisherman spread, and aquarium industry effects), and at the effects of controlling one species on the growth of other species. Some of us wondered if allelopathic responses offered any promise. Somewhere along here, I went over the wall, escaped from OCE, and followed Roger Hamilton's tracks to Fort Worth. And Lewis Decell said: "Send money."

My most vivid recollections about the program are these four things: the most severe problem, the biggest change to the program structure, the best reaction to a request for assistance, and what I contributed.

- Most severe problem: the fiscal year 1982 budget, when the Reagan Administration imposed a $1.5 million cut on what was then a less than $5 million dollar-program. We all learned a great deal about sharing by the time that year was over. It was right about here that Lewis Decell, and every other manager involved in the program really yelled: "Send money."

- Biggest change to program structure: establishment of the Aquatic Plant Control Support Center in the Jacksonville District. This provided an operationally orientated way of sharing expertise among Districts with newly emerging aquatic challenges. It offered the Corps an additional way of getting new ways of doing things to the field offices, which were confronting problems that were new to them.

- Best response to a request for help: the 1982 Large-Scale Operational Management Test for waterhyacinth control in the Sacramento River put on by the combined efforts of WES, the Aquatic Plant Control Support Center, the South Pacific Division and the Sacramento District, and the State of California. I believe that was one of our best demonstrations of existing and emerging technology in support of our non-Federal partners that has been done to date. It was done in an extremely condensed time frame and really got technology to the field rapidly, while gaining considerable support for the program. This was a great "partnering" effort, although we didn't use that catchword at the time.

- Best contribution I made: If I made a contribution to the program it was that I finally really listened to Lewis Decell, and to many of our folks in various Districts, when they all said: "Send money." We did some preliminary work with the staffs of Senator Chiles of Florida and Senator Stafford of Vermont to address their considerable interest in raising the statutory dollar limit on the overall program from

$5 million to $10 million. That change did occur in July 1983, shortly after I had departed for Fort Worth.

Now that I'm in Fort Worth I've learned to view events more and more from the field's perspective (although our folks at our lake projects constantly remind us that the District Office really isn't the field). So now I join Lewis Decell and all our field elements when they implore the chief's office and OMB to recognize their requirements for mission performance. In closing, I'll leave you with one thought: "Send money."

Significant Events
Aquatic Plant Control Research Program
August 1983-June 1989

by
E. Carl Brown[1]

Introduction

As requested by Lewis Decell, I will provide my perspective of the events and accomplishments in the Aquatic Plant Control Program during my term as Technical Monitor, from August 1983 to June 1989. My general topics will be changes in policy and law, program focus, and accomplishments.

The presentations by the speakers preceding me have shown that the Aquatic Plant Control Program, as with any good program, has continually evolved during the several years it has been in existence. The period I will be talking about was no different. It was a time of growth and changes in the program. Some of those changes we made happen; some were thrust upon us.

Policy and Law

In the area of policy and law, there was "good news and bad news." First, some of the good news. Section 104 of the River and Harbor Act of 1958, as amended, set a $5 million limit on annual appropriations for the Aquatic Plant Control Program. By the early 1980's, the program had grown to the extent that $5 million failed to cover the needs of planning, control operations, and research. Because of this, some friction had developed between the planning, control operations, and research proponents in regard to funding priorities. Fortunately, the Supplemental Appropriations Act of 1983 raised the annual appropriations limit to $10 million. The limit was again raised by the Water Resources Development Act of 1986, to $12 million. The authority to obtain more than $5 million annually for the program relieved the funding competition between the program elements.

The cost-share requirements for the Aquatic Plant Control Program set out in the Water Resources Development Act of 1986 (WRDA 86) and the implementation policy that followed caused some waves that have not yet calmed. WRDA 86 changed the cost share for control operations from 70 percent Federal/30 percent non-Federal to 50 percent Federal/50 percent non-Federal. Section 104 of the River and Harbor Act of 1962 (PL 87-874) had provided that costs for planning for aquatic plant control would be borne fully by the United States. WRDA 86 requires that all planning beyond the reconnaissance level shall be 50 percent Federal/50 percent non-Federal. WRDA 86 also imposed a requirement for a Local Cooperation Agreement to cover planning, and a different Local Cooperation Agreement to cover control operations. In addition, the implementation policy requires that the work plan in the Local Cooperation Agreement for control operations must be renewed each year. As many of you know, these changes were not received well by our State aquatic plant control program sponsors—especially those who have worked so diligently with us for many years. In spite of all these rough spots, the dedication and perseverance of our field people and our State sponsors held the program together, although we know they carry some scars from this period in the program evolution.

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Program Focus

By 1984, two things had happened. First, we were seeing more and more support voiced for the positive value of aquatic plants in the ecosystem. Second, I felt secure enough in my knowledge of the program to start promoting my ideas for program focus. So I made a strong pitch for moving toward a comprehensive program of aquatic plant management, rather than just aquatic plant control. We made good progress with this program focus between 1983 and 1989.

As a companion item to the comprehensive management philosophy, I pushed hard for strengthening the biological and ecological research work units. There was no question that the chemical, mechanical, and physical research elements were (and are) important, but I perceived that we were lacking in knowledge of life requirements of plants that may help identify new and innovative pathways to cost-effective control and management. There was some backlash from this effort. Apparently, my enthusiastic support for biological and ecological research made researchers in the chemical, physical, and mechanical areas feel left out.

This "left-out feeling" manifested itself in a presentation by a researcher from the Waterways Experiment Station at one of our annual program reviews. In that presentation, the researcher compared the Aquatic Plant Research Program to the plot in the Wizard of Oz. I never quite figured out whether my role in that comparison was the phony wizard, the wicked witch, or the scarecrow with no brain. Considering the options, I decided not to ask.

Researchers, please understand that I do recognize the importance of all facets of the Aquatic Plant Control Research Program. Clearly, effective management and control of aquatic plants is going to require wise use and integration of all the tools available—biological, ecological, chemical, physical, and mechanical.

Accomplishments

From August 1983 to June 1989, we were able to

a. Strengthen the ties between research products and operations and planning needs.

b. Reinforce the concept of aquatic plant management rather than just aquatic plant control.

c. Strengthen and expand the functions of the Aquatic Plant Control Operations Support Center. I commend Bill Zattau and Pete Milam for their successful efforts in this regard.

d. Establish an Operations/Planning breakout session at our annual program reviews to provide a forum for information exchange on successes and problems in planning and control operations.

e. Sustain cooperation with the chemical industry in testing and adapting chemical control agents for use on aquatic plants.

f. Improve some chemical control formulations.

g. Release personal computer-based simulation models (expert systems) for mechanical control operations and white amur stocking rates.

h. Release four insect control agents.

i. Field test successful combinations of fungus and bacteria for Eurasian milfoil control.

Conclusion

The period between August 1983 and June 1989 was productive. There were some anxious moments, but the program survived. It

survived because of the tenacity, professionalism, and teamwork of our sponsors, our Corps field people, the Corps and contract researchers, and cooperating industry representatives.

My thanks to Lewis Decell for his guidance and help while I was Technical Monitor. Lewis is a good manager. Working with him was and is interesting. You always know where you stand with Lewis. He will tell you if he doesn't agree with you, which in my case seems to be most of the time!

My thanks also to Darrell Lewis, Bill Rushing, and Jess Pfeiffer of HQUSACE for their help and support. Finally, my thanks to the Corps District and Division people, the researchers, and sponsors who supported and administered the program during my watch. It was a pleasure working with you. Keep up the good work. You are the best at what you do!

Significant Events
Aquatic Plant Control Research Program
1989-Present

by

J. W. Wolcott[1]

Now—for the "new person on the block." I started working with the Aquatic Plant Control Program in 1989, after Carl Brown left Headquarters for the Waterways Experiment Station. Let me say this: Carl Brown is a tough act to follow.

The 1989 program review in Huntsville was my first. It was an extremely stimulating event, especially when the tornado struck! What is the current hurricane status here in Florida?

I am honored to be part of the 25th meeting, and am especially glad that Darrell Lewis, Chief of the Natural Resources Management Branch in Headquarters, is here. Darrell is a strong supporter of the Aquatic Plant Control Program and will be here for the entire meeting.

Lewis Decell asked me to speak on my experiences since joining the program less than 2 years ago. My number one experience has been the development of an appreciation for your accomplishments. The Corps is the recognized leader in aquatic plant control technology development. You have accomplished this through partnerships—with other Federal agencies, state and local governments, industry, and other private sector partners. The ongoing Joint Agency Plan for Aquatic Plant Management on Guntersville Reservoir, a Corps-TVA research effort, is a highly visible testimonial to your partnership successes.

Through research, technology development, and technology transfer, on-the-ground control programs have evolved from simple chemical applications and harvesting efforts to sophisticated integrated programs. The integrated management techniques developed and implemented several years ago are "ahead of the curve" in comparison to other vegetation control programs. Your work with fish, insects, and pathogens is commendable.

Reducing alligatorweed and waterhyacinth to maintenance levels in the United States, introducing biological agents for the control of hydrilla and milfoil, and developing techniques that permit chemicals to be used more effectively and environmentally are major success stories. And, we are sure there are more to come. Incidentally, Darrell and I witnessed an unprecedented level of hydrilla control on the nearby Withlacoochee River yesterday.

What is the "Vision of the Future" for aquatic plant management? With new and expanding infestations, there is no shortage of research needs and opportunities in the future. Our biggest challenge will be funding, as Congress wrestles with the Federal deficit. We have about $1.5 million in unfunded capability in the combined research and cost-shared operations program in FY 91. In FY 92, we can probably expect the gap between needs and funded levels to remain, or possibly broaden. In a constrained resource environment, efficiency and money management will become even more important.

Another part of our vision is environmental management. Secretary of Defense Cheney said "This administration wants the United States to be the World leader in addressing

[1] Headquarters, US Army Corps of Engineers, Washington, DC.

environmental problems, and I want the Department of Defense to be the Federal leader in agency environmental compliance and protection." Mr. Stone, Secretary of the Army, and General Hatch, Chief of Engineers, wholeheartedly endorse this challenge.

This challenge offers the opportunity to intensify the focus on biological controls and integrated control programs, while helping the beneficiaries understand and support the value of past successes. I expect the Determining Economic Values of Aquatic Plant Management work unit to help in this regard. We also need to emphasize aquatic plant management by supporting wetlands restoration and development, fish and wildlife restoration, and other environmental initiatives.

Compliance with environmental laws and regulations should be a top priority in both research and control programs in FY 91 and the following years. We are developing an Environmental Review Guide for Operations (ERGO), to be distributed around the first of the year. This checklist will help operational managers determine their program strengths and weaknesses.

In conclusion, aquatic plant management is definitely a growth business (pun intended). Your combined research and operational efforts have produced tremendous benefits for this nation. Nowadays, 25 years is a long time for a relationship to survive, but this partnership of researchers and operators, and of Federal, state and local governments, colleges and universities, and the private sector, has strengthened as it has progressed through time, and it is destined to continue. Keep up the good work, and have a great "25th."

Program Manager's Perspective of Significant Events 1975-1990

by

J. L. Decell[1]

This is the 25th meeting of the Aquatic Plant Control Research Program. I have attended 18, and have been responsible for conducting the last 16. This particular meeting has more meaning for me than just the nature of the anniversary.

As the time to write my speech drew near, I began to think "What could I talk about that would be appropriate for such a significant meeting?" I decided that I would convey the program's growth over the last 25 years. But then I thought, what would I use as a true measure of that growth? Funding is an indicator, but money doesn't **assure** growth—it simply allows for growth and removes one excuse for lack of growth. I decided that funding was not an appropriate measure of our growth.

Next, I considered talking about the volume of technical information that has been produced. As I began to consider this, I was overwhelmed by the volume, and realized that even at my very best, I could not do justice to the quality of this technical information by using it as a basis for characterizing the program's growth.

I then thought of the possibility of discussing the continuity of our efforts. Although we have remained continually alert to the changing focus of interest and the varying nature of the problems addressed, we have maintained a consistency in our research that has served us, and others, well.

Not able to cover the entire program, I was then faced with the decision of which program element would best represent this continuity? Each technology area has maintained this continuity in its own right. No single technology area or research unit has more than another, because I have always evaluated them on their own merit, and their ability to meet their respective objectives.

So, if funding, technology, and continuity do not serve my purpose for this talk, then what? As I thought, two things became clear to me.

First, **growth** was not what I wanted to talk about at all! What I wanted to talk about is success! Funding, continuity, technological achievements, and even growth, are either contributing factors to, or the result of, **success**! The second factor is that the basis for the success is the people who made it possible—mainly you!

So I decided that if I talk about the **people,** and their **efforts** to respond to the often difficult guidance provided by management, I will not only convey the sense of the success of this program, but I will lay the credit squarely at the your doorstep where it rightfully belongs.

So, I decided that I would talk about you and me. "You" means everyone that I have come in contact with during my time as manager of the research program. I'll start by talking about me first. While that sounds selfish, it provides me the opportunity to set the stage for some things I want to say to you. And, I also don't have to end my talk on an apologetic note, if I offend myself!

1 US Army Engineer Waterways Experiment Station, Vicksburg, MS.

My first involvement with the program was conducting a research work unit for Headquarters to develop a CO_2 laser to control waterhyacinths. During this same time Bill Rushing was in Puerto Rico, and received funding to study some problem snails and their relationship to aquatic plants.

Later, I was assigned responsibility for the overall program and attended a meeting in Washington, called by the Chief of Civil Works of the Corps of Engineers, that was attended by everyone who had—or was going to have—involvement in management and oversight of the program. Among other things, the Chief of Civil Works stated that he wanted this program to be "Nationally known, without becoming a National issue."

At the time I did not appreciate what he meant, because I was too busy trying to determine the correct spelling for waterhyacinths.

My first commitment was to "market the program." With the support of Roger Hamilton, who was the new Technical Monitor, a reorganization at WES that provided visibility, and the help of Bill Rushing, I set about to market the Corp's Aquatic Plant Control Research Program to the Nation.

I was successful in obtaining non-research funds from Headquarters to conduct a public information program, and it remained in the program for 3 years. This may have been the only such effort in any research program in the Corps, before or since. I decided that we needed a logo to aid our visibility. Bill Rushing produced the first program-level logo in the Corps. It existed until 1988, when I retired it when Bill went to Washington.

After about a year, I realized that I was marketing the program to the wrong audience. I realized that if we were to obtain the funding adequate to provide the opportunities for success, I needed to market the program to the Corps of Engineers—not the entire Nation! The market in the Corps is the Districts, the users, the people with the problems, those who pay the bills!

As part of this marketing, I requested that Headquarters allow the research program review to be an integral part of this meeting, and also require the operations personnel to attend and give presentations on their operational problems.

It was about this time that I began to realize that in forming a long-range outlook, I was also, out of necessity, developing a philosophical basis for my actions.

I adopted the notion that a worthy overall purpose would be to conduct everything we did as if our objective was to "put ourselves out of business." While I realized it was (and **is**) an unattainable goal, it served as an unaffectable basis for evaluating decisions—before implementation.

It was also a constant reminder to me that if we did indeed "go out of business," it should be as a result of our own efforts, and not the result of Headquarters eliminating the unit!

I began to instill the philosophy that we should not be proponents of any particular type of control method, but could only be proponents of the way in which we conduct the research that provides the technology for those control methods.

In addition, I suggested that in recommending methods, each must stand on its own merit in the context of site specificity. Thus, no method should be promoted or accepted on the basis of promoting the disadvantages of a competing method.

I adopted the view that we have two things to do: we advance the state of the knowledge, and we advance the state of the art. For my purpose, I defined the difference between the two as simply **what we know**, and **how well we apply what we know.** Research certainly advances the state of the knowledge, and has a stake in the subsequent advancement of the state of the art. But it is the operations elements of the Corps that are the key to advancing the state of the art.

I soon began to view the criticisms by the field personnel in this context, and as a result, took their input in a more positive light. It provided me with a productive basis for overcoming existing sensitivities, and more significantly, focused my thoughts on what it really takes to develop and direct a true user-oriented research program.

I realized that, like it or not, part of my job was to satiate the researchers while satisfying the operations elements (Purvis, Joe, Bill Z.).

Over time, I have dedicated much of my effort to maintaining the APCRP to satisfy the operational needs, the researcher's visions, and Headquarters' views, without compromising these general philosophies. I hope they are now **our** philosophies.

And now to talk about you. In doing so, I am going to run the risk of naming names. The risk involved is not my fear of retaliation, but the risk of overlooking someone. I want you each to know that I am privileged be working with each of you. There are a representative few, however, that I want to mention for the record. First, the Technical Monitors.

Thank you, Roger Hamilton, for the initial support that allowed some of the early visions to become realities.

Thank you, Dwight Quarles, for the continuing support at a time of transition, which allowed us to maintain the momentum of our initial program, and for making the Operations Center a reality.

Thank you, Carl Brown, for your tireless honesty and dedication to first understand what it was all about, and then support it to proceed even farther.

Thank you, Jim Wolcott, for your patience and foresight to realize that it isn't broken, and your continued support.

Thank you, Gerald Purvis, for making me realize that support can come in many forms, and for our long association.

Thank you, Bill Zattau, for making the Operations Center the responsive reality that it was intended to be—advancement of the state of the art.

Thank you, Joe Joyce, for your contributions during those early years, when I learned about the things that I didn't want to know about. Thank you for sustaining.

Thank you, John Frizzell, for my continuing education on the complexities of industry that made me realize that the Government bureaucracy wasn't so bad. You see, I'm now a part of the bureaucracy—and I feel okay.

Thank you, Dr. Whalin and Dr. Harrison, for continuing to provide the rope—without the rope burns.

Thank you, Bill Rushing, for being the "great facilitator," for allowing me the luxury to be creative, and to test and implement ideas. It is evident that the APCRP would not be where it is today without your contributions, while you were at WES. Most of all, thank you for remaining my friend after 14 years of working for me.

Thanks to the Environmental Laboratory Group Chiefs who have supported the program by assuring the successful completion of the work of their researchers.

Last—and certainly most important—to the Environmental Laboratory researchers whose cooperative efforts make the word teamwork an inadequate descriptor.

I thank you for your dedication, your integrity, your guidance, your arguments, and your confidence, which provide me with the basis to envision and formulate our future direction.

Most of all, thank you for your patience. Increased funding, in itself, puts the pressure of responsibility to produce on responsible people. I have been very demanding in requiring results, and you have continually responded. As a result of your efforts in accepting this view, the APCRP has no equal in the development of nationally applicable technology for APC.

Periodically, during these last 15 years, in spite of my best efforts, I was overtaken by events. I want you to know that you have been overtaken by a major event—**success**—and I thank each of you for your contribution.

There are two kinds of people that are involved in research: those who manage what they do not understand (**me**) and those who understand what they do not manage (**you**).

I think this is our team. And I am honored to be a part of it.

Lewisville Aquatic Ecosystem Research Facility: Progress Report

by

R. Michael Smart[1]

Introduction

The USAE Waterways Experiment Station, under an agreement with the US Army Engineer District, Fort Worth, recently began operation of the Lewisville Aquatic Ecosystem Research Facility in Lewisville, TX. The facility consists of 55 earthen ponds and 18 flowing water mesocosms which are supplied with water from Lewisville Lake, a Corps reservoir immediately adjacent to the facility. The facility is being developed and used by the Aquatic Plant Control Research Program (APCRP) as a national center for conducting aquatic plant research. Research conducted at the facility will support each of the technology areas included in the APCRP. With the addition of this pond facility, the APCRP now has an intermediate-scale research environment that will facilitate the extrapolation of laboratory-derived technology to the solution of real-world problems.

Facilities

Renovation of the laboratory building, which was begun in fiscal year (FY) 1989, was continued in FY 1990, with the addition of an office wing containing three offices and a small meeting room. The two laboratories are being furnished and equipped based on immediate needs and availability of funds. Plans are to have the laboratory equipped for processing and analyzing of plant, water, sediment, and fish samples by the end of FY 91.

Renovation of the ponds is continuing at a pace dictated by the demand for ponds, their condition, and the availability of funds. The number of fully functioning ponds currently exceeds our estimates of APCRP demand for the next several years. Excess ponds will be made available for aquatic and wetlands research to WES, other Federal and state agencies, and colleges and universities on a space-available, pay-as-you-go basis.

One of the mesocosm facilities has been converted to a greenhouse containing six flowing-water, concrete raceways measuring 20 by 3 by 2 ft deep. These mesocosms are equipped with flowing lake water and can be used for conducting flow-through studies or smaller scale studies to supplement larger scale work in the ponds. These systems have been used for maintaining large numbers of waterhyacinth plants through the winter period.

A meteorological station has been collecting data for over 1 year, and several of the ponds have been equipped with data loggers and environmental monitoring equipment for obtaining continuous records of environmental conditions in the ponds. Facility personnel are also collecting water quality data (pH, dissolved oxygen, conductivity, and temperature) weekly. All of these data are available in digital form to researchers using the ponds.

Personnel

The full-time staff now includes three scientists, three graduate contract students, and one undergraduate contract student. Dr. Gary Dick is working with us through an intergovernmental personnel act agreement with the University of Southern Mississippi. Gary is managing the ponds and the physical

[1] US Army Engineer Waterways Experiment Station, Lewisville Aquatic Ecosystem Research Facility, Lewisville, TX.

facilities. Dr. John Madsen is working with us through a delivery contract with ASci Corporation. John is an aquatic plant ecologist conducting research on the phenology of aquatic plants, primarily waterhyacinth. The author has relocated from WES in Vicksburg, MS, to the Lewisville facility to direct the expanding research activities there and to conduct research on competitive interactions among introduced and native species of submersed aquatic plants.

Research Activities

The facility is currently supporting research in most of the technology areas of the APCRP. Biological control is represented by a field test of a commercial formulation (mycoherbicide) of a microbial pathogen, *Mycoleptodiscus terrestris*, developed by EcoScience in cooperation with WES researchers. Ecological technology is being developed in studies of the effects of *Hydrilla* populations on fish production and in studies of competitive interactions among native, nonweedy species and introduced, weedy species of submersed aquatic plants. Applications technology is being developed in studies of the efficacy and environmental effects of benthic barrier application for control of submersed aquatic plants and in studies of the phenology of waterhyacinth. Simulation technology is being developed by a cooperative expansion of the study of waterhyacinth phenology to include aspects of production biology and ecology which are needed for validation and improvement of an operational model incorporating a waterhyacinth growth simulation module. Chemical control technology will benefit from studies currently being planned for conduct at the Lewisville facility. These studies will likely include field tests of efficacy and environmental effects of chemical controls as well as methods for using existing chemical controls to achieve species-selective control.

Since the available facilities at Lewisville exceed the current research needs of the APCRP, unused ponds will be made available for other aquatic and wetland research efforts. The ability to completely control the hydrology of the ponds makes them ideally suited for a variety of aquatic ecosystem, water quality, and wetland studies.

Information Exchange

An information exchange bulletin describing the facilities and capabilities of the LAERF was published. A color brochure describing the facility and its intended use for aquatic plant and aquatic ecosystem research related to the mission of the Corps of Engineers was also produced. These items are available from the author or from the Manager of the ERRAP, WES.

Valuation of Aquatic Plant Economic Benefits

by
Jim E. Henderson[1]

Aquatic plant control programs produce economic benefits through increases in the public goods and services supported by aquatic plant control. The need to quantify economic benefits for use in planning and management decisionmaking is being addressed by the Economic Values of Aquatic Plant Control Work Unit, part of the Guntersville Lake Joint Agency Project being conducted by the Tennessee Valley Authority (TVA), the USAE District, Nashville, and the Waterways Experiment Station (WES). The objective of this work unit is to incorporate economic valuation techniques into aquatic plant programs.

The total economic value of natural resource management programs, such as plant control, is the sum of the value of the services resulting from operation of the resource. Goods and services supported by aquatic plant control include such things as navigation, flood control, hydropower, and recreation (Figure 1). The intent of economic analysis is to identify and quantify the benefits and costs for each of these services. The objective of considering economic costs and benefits is to provide for better decisions through consideration of all impacts and benefits and costs. Economic analysis requires identifying the public's perceptions of aquatic plants and aquatic plant problems, preferences for control measures, and valuation of different control alternatives.

The intent of this work is to provide planning and operations personnel with ways to quantify costs of aquatic plant problems and the benefits from aquatic plant management, thereby providing a better basis for decisionmaking.

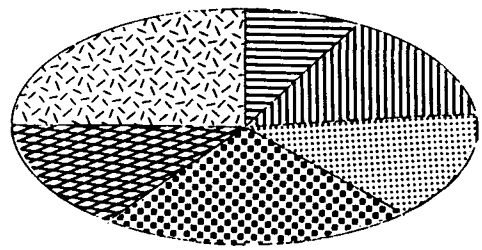


Figure 1. Total economic value

Literature Review

Early in fiscal year 1990, a literature review was performed by Dr. Eric Thunberg of the University of Florida. The review examined reports and documentation from Corps, state agencies, and academic interests to determine how economic costs and benefits were addressed. Overall, economics was addressed in a cursory manner, if at all. Recreation benefits were addressed most often. However, some of the recreation benefits were addressed without good information on recreation use, preferences, or recreation demand. Many studies focused on losses in benefits from the authorized purposes of the project. That is, for a navigation project, all benefits from control or losses due to aquatic plant were considered navigation benefits and losses, ignoring the recreation and other services provided or affected by aquatic plants. In all cases, the benefits estimation procedures were not well documented.

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lake Guntersville

Lake Guntersville is the study area for applying economic methods to aquatic plant management. The lake is a 70,000-acre impoundment on the Tennessee River in northeastern Alabama. Guntersville is part of the Tennessee River navigation system, supporting movement of grain and other agricultural products, as well as coal.

The lower end of the reservoir is formed by a number of inflowing creeks which form extensive shallow embayments popular for fishing, waterskiing, and pleasure boating. The shallow embayments are also highly suitable for growth of aquatic vegetation. Boating access is supported by about 35 boat ramps, 20 marinas, and numerous other access points. The upper end of the reservoir is more riverine in character, with fewer developed facilities and more dispersed or informal use. There are over 50 subdivisions along the shoreline, with over 3,000 lots. Many of these homes have boat houses with direct access to the lake.

Two studies are under way at Lake Guntersville—a Recreation Study and a Land Values Study. Beginning in February, a yearlong survey will be undertaken to determine the impact of aquatic plants on recreation and recreation benefits, and to determine perceptions of aquatic plants. The Land Values Study is intended to determine the relationship of aquatic plant infestations to the value of residential property.

Recreation Study

The recreation survey will interview recreation users at marina, ramp, campground, and dispersed or informal use areas. A separate residential survey will be initiated later in the year. The purpose of the Recreation Study surveys is to determine (1) perceptions of aquatic plants, (2) perceptions of aquatic plant control, and (3) valuation for recreation under different aquatic plant conditions.

Surveyors will ask recreators about their recreation use, including recreation activities and amount of use (e.g., length of stay, how recreation is affected by aquatic plants, and perceptions of aquatic plant problems and preferred levels of control). Two important questions are the following:

How would you describe the aquatic plants' impact on your recreation activity today?

A. A help

B. Doesn't affect my activity

C. Bothersome only sometimes

D. Bothersome most of the time

E. Don't know

What amount of aquatic plant coverage would you like to see?

A. As much as possible

B. Somewhat more than presently exists

C. The same as presently exists

D. Less than presently exists but at least some

E. No coverage; eliminate the plants

F. Don't know

Responses to these types of questions give an indication of perceptions of impacts on recreation activities and perceptions of desired levels of plants. Looking at these responses broken down by the recreation activities (e.g., fishermen versus pleasure boaters) helps determine the differences in preferred amount and location of plant coverage. In this way, consensus and conflicts between user groups are identified.

The fishing at Guntersville has received much publicity in sports fishing circles, with attention to the benefits of aquatic plants for fish habitat. For this reason, a section of the questionnaire elicits perceptions from fishermen

about the perceived relationship of aquatic plants to the size and abundance of fish, preferences for large or small patches of aquatic plants, and the need for management of aquatic plants.

The recreation surveys will be administered face-to-face at campgrounds, boat ramps, and other access points. At the conclusion of the interview, the respondent will be given a survey form to take home and return by mail. The mailback survey is an Expenditure Survey and collects information on the trip expenditures, e.g., camping fees or lodging costs, for the trip to Guntersville. A second part of the Expenditure Survey collects information on yearly expenditures for recreation, such as equipment, boats and fishing tackle, and insurance. Data collected from the Expenditure Survey will be used to determine the economic impact of recreation at Guntersville.

The benefits and costs of public programs are used to evaluate the extent to which programs are effective in meeting objectives, and in some cases whether the programs exist at all. Recreation sometimes has difficulty in competing with other project purposes because of the nonmarket nature of recreation experiences and benefits, and lack of experience with estimating recreation benefits. For recreation, economic benefits arise from people's willingness to pay (WTP) for recreation.

The WTP concept is used for nonmarket valuation of nonmarket goods and services, that is, for recreation, aesthetics, and for other public goods and services that exist and are valued by people but are not traded in a market. This is contrasted with navigation benefits, where the benefit is taken as the cost savings in transportation costs of waterborne versus rail or highway transport. Similarly, for flood control, benefits represent the amount of annual flood damages prevented. Flood control and navigation benefits can be readily determined because of the market nature of the services provided by navigation and the goods incorporated in flood control losses.

In cases such as aquatic plant control or other changes in natural resources, the appropriate method of determining benefits is the Contingent Valuation Method (CVM). The CVM method is used to elicit values for WTP from respondents by posing or describing a scenario of resource conditions and having the respondent state (1) their recreation use under those conditions and (2) their WTP for recreation under the conditions of that scenario. In the case of aquatic plant control, scenarios may include descriptions of aquatic plant coverage and distributions, fishing success, number or type of fish caught, or frequency of interference with boat operations caused by aquatic plants.

In order for respondents to the CVM survey to give reliable WTP and judgments on their changes in recreation use, it is critical that the control alternatives be presented in realistic terms that respondents could easily relate to and understand. Three acreage coverages could be included in the CVM scenarios: historical high plant coverage in 1988 of 20,000 acres or 21 percent of the reservoir; current (1990) conditions of approximately 11,000 acres; and stated goal of the Joint Agency Project to manage at no more than 7,000 acres or 10 percent of the reservoir.

In anticipation of preparing scenarios for the CVM survey, it was apparent that information was needed not only on potential acreages of plants, but also on where the plants would be located in the lake. In terms of recreation access and recreation use, the distribution of plants may be of greater importance than absolute number of acres. To obtain technical guidance on how to portray the distributions in the CVM questionnaire, the Technical Advisory Panel (TAP) was formed. Representatives of those disciplines or interests that are affected or supported by aquatic plants or control activities were included (water quality; fisheries; recreation; waterfowl, wetlands, and wildlife; and aquatic plant control). A TAP meeting was held in Huntsville, AL, on November 6-7.

TAP members were academic, private sector, and state agency personnel (not part of the Joint Agency Project). Their charge was to develop a plant distribution map for the reservoir, taking into account the multiple disciplines that are involved. This was accomplished in a number of steps. Each discipline or group first developed a set of criteria or rationale for the distribution of plants in an area. The Water Quality and Aquatic Plant Control groups used criteria for not controlling or not wanting plants, such as near water supply intakes and in front of shoreline development, public use areas, and mosquito control areas.

Ideally, the distributions could have been digitized on a Geographic Information System (GIS), greatly increasing the ease of the process. While this capability will be available later in the project, the GIS capability is not currently available. (For instance, a GIS layer on bathymetry, or water depth, would have assisted the groups in determining how far into the river the plants would invade before reaching water too deep for rooted vegetation (about 6 meters).) However, the TAP groups had to use the navigation charts which delineate the navigation channel (15 feet). Having the groups mark plants on maps of the reservoir is clearly a rudimentary way to accomplish the work, but was required due to the timing of the CVM surveys.

Using the criteria as a guide, the groups marked maps of the reservoir to show plant distributions. The groups used three priority classes for the plant distributions, indicating the importance or desirability of having plants, thus accommodating the need to show varying acreages of plants. The marked maps appeared as the large areas of the highest priority for plant distributions, encircled by areas of less priority. These representations showed that a core amount of plants would grow in areas, the extent of the core areas determined by control efforts and natural fluctuations in water levels and other growth determinants, e.g., nutrient input.

The groups made presentations of the five distribution maps, explaining the rationales for optimal distribution. Using a dot grid counter to approximate acreage, the optimal distributions ranged from a 7,000-acre minimum for the Recreation group to approximately 15,000 acres (Priority I and II) for the Fisheries group. There was a great deal of overlap for the distributions, but also many points of conflict between groups.

Specific recommendations or criteria of interest include:

a. **Aquatic Plant Management**—No plants near shoreline developments, a 150-foot clear swath to be maintained in front of priority areas of shoreline development, public use areas, and mosquito control areas.

b. **Water Quality**—One mile clear of plants on each side of water intakes; effects of wind-induced waves and currents during storm events require this level of control. Plants should be distributed to improve water quality (specifically, plants should be left in areas of high nutrient input, since algal blooms would occur without the macrophytes) and to trap sediments and pesticides from agricultural runoff; plants should also be left near a paper mill and steam power plant for uptake of heavy metal and organic constituents.

c. **Wildlife, Waterfowl, and Wetlands**—Plants should be maintained in the wildlife management areas, located in the upper end of the reservoir, and near caves. Preferred areas for wildlife and waterfowl are away from municipal, residential, or industrial areas; the wildlife distribution map had few plants on the more developed lower end of the reservoir.

d. **Fisheries**—Improvement of fishery by managing smaller contiguous mat areas; cutting numerous boat lanes;

and management for a diversity of fish species.

e. **Recreation**—Maintaining access, preserving aesthetics, and controlling plants along developed shorelines, near boat ramps, and along residential home lots. Waterskiing and pleasure boating are primarily on the embayments of the lower end, but some vegetation should be left for edge effect and to benefit wildlife.

At the conclusion of the presentations, the groups developed a consensus distribution map by identifying the conflicts between the five distributions. Trade-offs between groups were accomplished through discussions about criteria and rationales for controlling or not controlling plants in specific areas. A consensus distribution map was prepared, representing all the trade-offs between the groups. Using a dot grid and manually counting the consensus plant distribution, there was approximately *14,000 acres of plants*. The consensus distribution map is being digitized at TVA for accurate determination of acreage, and is being corrected for such things as lake areas that are too deep for plants or other constraints not represented on the maps.

The consensus distribution map, with priority areas marked, will be used in formulation of the CVM scenarios. When draft scenarios have been prepared, they will be circulated to TAP members for review and comment so that the surveys will use plant distributions and acreages that are relevant to the lake users' use and valuation of their recreation experience.

To summarize the Recreation Study, the onsite surveys will be used to estimate the existing recreation use of the lake, and to gather information on perceptions of aquatic plants and aquatic plant problems. The mailback Expenditure Survey, given to the onsite respondents, will be used to collect data on the trip expenditures for recreation users of Guntersville Lake and the annual expenditures for equipment, such as boats, fishing tackle, fishing licenses and hunting leases, and other recreation expenditures associated with more trips than just the one visit to Guntersville. The expenditure data will assist in determining the economic impact of recreation at the lake.

The CVM surveys will use different management or control alternatives to elicit how the recreation use will change and what the recreator's WTP will be for the different alternatives. Through collection of WTP information, the economic benefits of different control alternatives are determined.

Land Values Study

The purpose of the Land Values Study is to determine the effect of aquatic plant infestations on residential land values. At Guntersville, a Hedonic analysis is being used to determine the effect of aquatic plants on residential land values. The Hedonic Approach is an economic valuation method used to relate changes in market value to the natural resource attributes affecting market values. This is basically a regression analysis relating changes in market values to changes in aquatic plant conditions over the years.

This analysis requires several data sets that are being assembled. A database of the over 3,000 lots around the reservoir is being compiled from the tax maps. A sample for analysis will be drawn from this database. For development of a model, measures are needed of total annual coverage as well as lot-specific coverage; this information will come from photo-interpretation.

At this point, the model development for aquatic plants is being examined. Hedonic analyses in the past have been used for valuation of natural resource characteristics such as wetlands preservation and water quality, where the change in natural resources was unidirectional, either exclusively increasing or decreasing. For aquatic plants, the acreages increase and decrease; the change is not unidirectional, making the modeling process more complicated.

Further Work

With the Recreation Study surveys under way, the next work effort will be to look at those other economic services that are affected by aquatic plants. For example, hydropower intakes that are clogged by aquatic plants result in increased costs for power production. These and other changes in project operations caused by aquatic plants will be identified to determine how economic benefits change as a result of aquatic plants and aquatic plant control.

Summary

The objective of the Economic Values work is to apply economic analysis methods to aquatic plant control programs. This requires gathering information on public perceptions and preferences on aquatic plants and control efforts, as is being accomplished through the onsite surveys. Determining the total economic value of aquatic plant control requires looking at all economic goods and services affected by aquatic plants. The Land Values Study and the upcoming work looking at other affected services, such as hydropower, will cover the range of impacts of aquatic plants on economic benefits. The results of these efforts will be formalized into guidance for valuation of aquatic plant control, with the overall objective being that aquatic plant control programs can be evaluated considering the range of goods and services, costs, and benefits affected by aquatic plants and control efforts.

Video Imaging Project for Aquatic Plant Mapping

by
Wayne T. Jipsen[1]

Introduction

Throughout the history of aquatic plant control efforts, field-level managers have been faced with several problems inherent to the basic ecosystem in which those efforts were conducted. Major problems included location of target species, quantification of plant populations, and evaluation of treatment efforts on those populations. Today's manager faces these same problems, in addition to the added challenge of accomplishing an increasing workload with decreasing budgets and manpower.

The problems associated with locating target species take several forms. Floating plant (waterhyacinth and waterlettuce) populations are coming under maintenance control in many areas of the southeastern United States. This presents the new problem of locating smaller populations of the target species over a wide area of responsibility. Submersed species such as Eurasian watermilfoil and hydrilla are spreading in many areas of the country. One of the most effective and cost-efficient control techniques for these two species is to locate and treat pioneering populations prior to their rapid expansion into the water body.

Quantification of floating plant populations on the water and of submersed species populations within the water column is much more difficult than the estimation of terrestrial populations. The potential for movement of floating plants presents the problem of redistribution of the population from one area of a water body to another. Delineating the limits of a submersed plant population is an essential first step in planning treatments as well as predicting budgetary and manpower requirements.

Once aquatic plant populations have been treated, managers must evaluate those treatments to determine their effectiveness and to schedule any follow-up treatments that may be necessary to control the target species. This evaluation process faces the same inherent problems as the original location and quantification phases.

Project Background

A work unit was created and a search was conducted to evaluate a technological approach to finding a solution to these problems. On 29 September 1989, a contract was awarded to Enviroscan, Inc., to develop an aerial imaging system and train selected field personnel in its use. Three initial sites were chosen for the demonstration and evaluation of the system. Those sites and their primary intended uses for the system were:

- **Lake Barkley** (Nashville District)—locate, identify, and quantify submersed aquatic plants in late spring to assist in the formulation of treatment plans for the summer season.

- **Lake Okeechobee** (Jacksonville District)—locate, identify, and quantify floating plant populations on a regularly scheduled, year-round basis; quantify and evaluate ongoing treatment operations.

- **Lake Seminole** (Mobile District)—locate, identify, and quantify submersed,

[1] US Army Engineer District, Jacksonville; Jacksonville, FL.

emergent, and floating plant populations for planning and evaluation purposes.

Water Watch systems were installed at the three selected projects during late March 1990. This was followed by a 3-day training session for all participants at the Natural Resources Office - Clewiston, FL, on 28-30 March 1990.

Materials and Methods

The Water Watch system developed under this contract utilizes a combination of the following hardware and software items:

- Personal computer with mouse
- Artist illustrator board
- Water Watch Software
- Black-and-white VHS video camera
- Lens and filter system
- Four-head video recorder
- Power converter to allow use from 12-, 24-, and 110-volt power sources
- Sony video monitor

By following a strict series of protocols (defining the desired report content, planning and executing the flight, performing the laboratory analysis, and producing the final report), the operator is able to gather and process the data in the most efficient manner. During the planning process the operator takes into account various details necessary to ensure data integrity.

During the data collection phase, the Water Watch flight system is installed in an airplane and flown over the target areas. Data are collected on VHS video tape using a preselected camera, lens, and filter combination.

In the laboratory, the data are processed in accordance with the predefined protocol for that flight. Using the software program to false-color the data ranges corresponding to the targeted plants, the operator is able to locate and quantify populations of that target species.

Results and Discussion

Several obstacles have prevented full testing and evaluation of the Water Watch system to date. During the data processing phase of the earliest flights, several software problems became evident. A contract with Enviroscan, Inc., to correct these problems was signed in the fall of 1990, and the software enhancements are scheduled to be delivered in early 1991.

The first enhancement will integrate a mouse-driven masking routine into the program. This will allow the operator to mask unwanted data from the screen prior to the quantification process. Without this routine, problems were experienced with the overlap of aquatic and terrestrial vegetation profiles. This manifested itself in the form of increased acreage counts in areas such as lakeshores, riverbanks, and islands where both vegetation types existed on the same data collection screen.

The second major improvement in the software will provide automated digitalization of set transects. This option should greatly decrease the amount of time needed to process the data from a given transect while increasing the accuracy of those data. In the original version of the software, the operator had to stop the video at each screen frame and process the data. This process was very time consuming on long transects and, since frame alignment was manual, accuracy was greatly affected by the individual operator.

While these problems have slowed the evaluation phase of this demonstration project, some flights have been undertaken, and baseline data are being gathered. Utilizing the system as a tool to aid in target species location is

the easiest application of its potential uses. This allows the operator more freedom in the use of camera angles to enhance the data-gathering abilities of the video equipment.

As a tool for quantification of target species populations, the upcoming software enhancements should greatly improve the program's capabilities. Both efficiency (in the form of speed of data processing) and effectiveness (in the form of greater accuracy) will be increased.

Increased operator familiarity brought on by experience will also improve the system's capabilities to be better tested. As operators at each demonstration site continue to evaluate the system, they will learn and share shortcuts and improve their own data interpretation techniques.

Summary and Future Work Planned

The Water Watch system as developed by Enviroscan, Inc., is in the early stages of evaluation. Upcoming software enhancements will greatly increase the system's efficiency and effectiveness. Results of early tests are mixed (as reported by the three test sites), but all demonstration sites felt that the system has potential and will require further testing.

Further study is needed to determine the optimum lens/filter combination for use with the various target plants. Seasonal variation in plant physiology, contrasts to adjacent plant populations, and seasonal water quality changes are some of the factors that need to be considered. As more studies are conducted in these areas, a larger selection of filters should become available to the Water Watch system operator. Development of additional filters will allow the operator to key on those plant properties or ecological parameters that will provide maximum contrast between target and nontarget species.

Water Watch equipment and technology have already been adapted to other natural resource tasks at several of the demonstration sites. Shoreline management activities, documentation of encroachments, timber and land management, wetlands management, and vegetation inventories are some of the fields into which this system can be adapted at the project level in the future. Expansion of system use into other management areas will increase the cost effectiveness of the equipment and may allow a wider range of projects to incorporate its use into their overall management strategies.

Acknowledgments

I would like to acknowledge the following individuals for their contributions to the technical evaluation of the Water Watch system: Lewis Decell, Jack Stoll, Rick Sinclair, and Mark Graves (US Army Engineer Waterways Experiment Station), Maurice Simpson (USAED, Nashville), Wayne Lanier and Sam Coward (Lake Barkley Demonstration Site), Joe Kight and Don Morgan (Lake Seminole Demonstration Site), Bill Zattau (USAED, Jacksonville, APCOSC), and Ron Miedema (Lake Okeechobee Demonstration Site).

Ecology of Submersed Aquatic Plant Species

History and Overview of Corps of Engineers-Sponsored Advances in Aquatic Macrophyte Ecology

by
John W. Barko[1]

Introduction

Research within the ecological technology area of the Aquatic Plant Control Research Program (APCRP) over the past 10 years has been directed primarily toward determining the response of submersed aquatic macrophytes to environmental factors. A variety of environmental factors interact in affecting the productivity, distribution, and species composition of submersed macrophyte communities. Foremost among these are light, water temperature, nutrients (including inorganic carbon), and sediment composition.

During the past 5 years, ecological research within the APCRP has been expanded to consider complex interactions among environmental factors and submersed macrophyte growth. Most recent studies have focused on mechanisms whereby submersed macrophyte communities influence environmental conditions. It is now apparent, based on results of field as well as laboratory investigations, that submersed macrophytes play an active role in affecting environmental conditions.

The purpose of this article is to provide an overview of major Corps-sponsored advances in aquatic macrophyte ecology, based on research activities in the APCRP during the past 10 years. In addition, this article summarizes current research activities and highlights results of studies reported in greater detail elsewhere in this proceedings.

Light and Temperature

Light is important in determining macrophyte morphology and distribution (with latitude, season, and depth), thereby influencing productivity and species composition as well. Differences in the morphological and/or physiological adaptability of submersed macrophyte species to various conditions of irradiance partially account for the greater competitive ability of some species compared with others in aquatic systems. In this connection, species capable of concentrating photoreceptive biomass at or near the water surface in low-irradiance environments are able to competitively displace species possessing relatively prostrate growth forms. Among the species examined in this laboratory, both *Elodea canadensis* and *Vallisneria americana* appear to be disadvantaged in aquatic systems characterized by low water clarity because of their limited elongation potential. Conversely, *Egeria densa, Hydrilla verticillata, Myriophyllum spicatum*, and *Potamogeton americanus* possess a significant ability to form a foliar canopy at the water surface.

Most submersed macrophyte species demonstrate increased growth with increasing temperatures up to at least 28° C. By reducing the length of the growing season, low temperatures effectively diminish the growth capacity of most (but not all) submersed macrophytes. Considering the distribution of submersed macrophytes in North America,

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

lower temperature limits in combination with basic differences in phenology may account for variations in the latitudinal range of many species.

The potential for aquatic systems to support excessive submersed macrophyte growth generally increases from north to south in the United States because of the respectively increasing favorableness of temperature conditions. Superimposed on this latitudinal gradient, conditions of both high light and high temperature at the water surface provide a maximum-growth environment for species capable of accessing the water surface. For this reason, even in northern localities, macrophyte species that effectively concentrate biomass at the water surface are potentially more productive than other species restricted to lower positions in the water column.

Nutrition

From research conducted in this laboratory and elsewhere, it is now generally accepted that rooted submersed macrophytes obtain nitrogen, phosphorus, and micronutrients primarily by direct uptake from sediments (Table 1). The role of sediment as a direct source of these elements for submersed macrophytes is ecologically quite significant since they are normally very low in concentration in available forms in the open water of aquatic systems. Considering the usual abundance and conservative nature of other major elements in the open water of most aquatic systems, it is unlikely that low concentrations of these nutrients directly limit growth of submersed macrophytes.

Table 1
Primary Sources of Nutrient Uptake by Submersed Aquatic Macrophytes

Nutrient	Source
Nitrogen	Sediment
Phosphorus	Sediment
Iron	Sediment
Manganese	Sediment
Micronutrients	Sediment
Calcium	Open water
Manganese	Open water
Sodium	Open water
Potassium	Open water
Sulfate	Open water
Chloride	Open water

Only in recent years has adequate attention been directed toward the importance of inorganic carbon supply in relation to the growth of submersed macrophytes. Significantly, the photosynthetic potential of a variety of submersed freshwater macrophytes appears to far exceed photosynthesis determined at ambient levels of available carbon in water. Studies in this laboratory have demonstrated significant increases in the growth of both *Myriophyllum spicatum* and *Hydrilla verticillata* under experimental conditions of increased carbon supply. Thus, considering the frequently high availability of nutrients other than carbon to submersed macrophytes, inorganic carbon supply potentially limits macrophyte productivity in freshwater systems.

Sediment Composition

Sediment composition (by affecting nutrition) has a pronounced influence on the growth of submersed macrophytes. In general, growth is relatively poor on both highly organic sediments and sands, as compared with fine-textured inorganic sediments. Poor growth on sands is related to high sediment density and, on organic sediments, to low sediment density. High concentrations of organic matter in sediments negatively affect the growth of submersed macrophytes, by reducing sediment density and the associated availability of essential nutrients (notably, N, P, and Fe). These elements are likewise low in available concentrations in sandy sediments. Thus, mechanisms of growth regulation on sand and organic sediments are similar; both involve nutrition.

Sedimentation of inorganic materials provides a nutritionally favorable environment for the growth of submersed macrophytes. Inorganic sedimentation is frequently accelerated by human activities in the watershed. For reasons that remain unclear, such systems are most susceptible to the invasion and subsequent explosive growth of introduced

macrophyte species. Once such an invasion has been initiated, the strengths and weaknesses of the native vegetation relative to those of the invading species ultimately control the direction of plant succession. In view of these findings, it appears that watershed disturbances, direct mechanical disturbances of bottom sediments, or autogenic processes affecting the inorganic/organic composition of sediments may contribute fundamentally to vegetational changes in aquatic systems.

Macrophyte Effects on Sediment Deposition

Sediment deposition is important to macrophyte growth. This process can refurbish nutrients lost due to root uptake or diffusional processes, and provides new substratum potentially available for macrophyte expansion concomitant with reductions in water depth. Sediment deposition, by altering the benthic habitat, may also influence the distribution and taxa of benthic invertebrates present. We have investigated the influence of submersed macrophyte communities on patterns of sedimentation both in a north-temperate system (Eau Galle Reservoir, Wisconsin) and in the Potomac River near Washington, DC.

In Eau Galle Reservoir, submersed macrophytes play an important role in promoting sedimentation and reducing sediment erosion, thus enhancing the stability and growth potential of these plants. In the Potomac River, sedimentation during the growing season is minimal in macrophyte beds compared with the open water. This is largely due to restricted movement of water and sediment into the beds. However, despite reduced rates of sediment deposition during periods of peak macrophyte abundance, deposition occurs uniformly across the bed into the open water during off-seasonal periods of high flow and turbulent mixing. With the recurrence each year of preseasonal sediment and associated nutrient deposition, conditions in the Potomac River appear to be ideal for the continued vigorous growth of submersed macrophytes.

Convective Hydraulic Circulation

On a daily basis, shallow nearshore regions of aquatic systems typically heat and cool more rapidly than deep open-water regions, due primarily to differences in mixed volume. The presence of submersed macrophytes in shallow regions contributes to the development of thermal gradients in both the vertical and lateral planes, since foliage near the water surface converts solar irradiance to heat. Thermal gradients give rise to density gradients that promote hydraulic circulation.

Implications of hydraulic circulation driven by convection are potentially far-reaching, since dissolved constituents can be moved with water. Dissolved constituents may include nutrients, contaminants, or herbicides. In the case of nutrients, it is important to determine the extent to which hydraulic transport from the littoral zone of aquatic systems may contribute to pelagic nutrient budgets, thus potentially influencing phytoplankton dynamics. In the case of herbicides, information on the periodicity of hydraulic transport would be of value in maximizing both the efficiency and effectiveness of treatment applications.

In Eau Galle Reservoir, dye studies have been conducted in combination with close-interval thermal monitoring in an attempt to evaluate the seasonal dynamics of convective circulation. Owing to the eutrophic nature of this impoundment, the focus has been on phosphorus transport. However, the results apply to all dissolved constituents, including herbicides. During studies conducted in 1988 and 1989, the littoral zone of Eau Galle Reservoir typically cooled more rapidly at night than the pelagic zone, creating horizontal temperature gradients resulting in convective water circulation. Water from the littoral zone moved into the pelagic zone as an interflow, while water from the pelagic zone moved into the littoral zone as a surface

flow. These results indicate the potential significance of macrophyte beds in affecting chemical budgets in aquatic systems. Currently, this line of investigation is being expanded to Guntersville Reservoir, Alabama, where emphasis will be placed on herbicide transport.

Future Initiatives

Past investigations have demonstrated that sediment fertility, influenced by a variety of factors (see Barko 1991) has an important influence on submersed macrophyte production and species composition. Nitrogen is a key element for the growth of rooted macrophytes. Thus, advances in our understanding of factors regulating sediment nitrogen availability will be of great value in the future development of management approaches based on reductions in sediment nutrient availability. Toward this end, the role of submersed macrophytes in the nitrogen economy of aquatic systems will be investigated.

In addition, a wide variety of physical and biological processes potentially contributing to the nitrogen nutrition of these plants will be evaluated. Laboratory studies will continue to focus on effects of sediment fertility on the growth of submersed macrophytes. In these studies the rooting depth of a variety of species is currently being examined. This information will be of value in assessing the extent to which species with different rooting depths may respond to sediment scouring or other forms of nutrient loss from surficial sediment.

Interactions will be examined among invasive and native macrophyte species in relation to sediment characteristics influencing fertility. Results of these studies will facilitate the design of more complex studies of long-term changes in macrophyte community composition to be conducted at the Lewisville, TX, pond facility and elsewhere. The feasibility of lessening sediment nutrient availability to macrophytes by chemical and biological means, and thus retarding the growth potential of nuisance species, will be investigated. As an extension of this effort, the possibility of perpetuating reductions in nutrient availability to nuisance species by interplanting preferred native macrophyte species will be examined.

Another line of investigation, addressing factors that contribute to both the invasion and decline of submersed macrophytes, will be initiated. The rate and extent of invasions by these plants are known to vary considerably among lakes, but specific factors contributing to invasions remain unknown. Likewise, naturally occurring declines of established populations of submersed macrophytes have been commonly reported, but the causes of these declines remain uncertain. Studies will be initiated to (1) identify environmental factors associated with naturally occurring invasions and declines, and (2) evaluate the potential for manipulating natural processes to reduce susceptibility to invasion by nuisance species or to encourage their decline.

Bibliography[1]

Barko, J. W., and R. M. Smart. 1980. Mobilization of sediment phosphorus by submersed freshwater macrophytes. *Freshwater Biol.* 10:220-238.

Barko, J. W. 1981. The influence of selected environmental factors on submersed macrophytes - a summary. Pages 1378-1382 in Proceedings of ASCE Symposium on Surface Water Impoundments, Minneapolis, MN.

Barko, J. W., and R. M. Smart. 1981a. Comparative influences of light and temperature on the growth and metabolism of selected submersed freshwater macrophytes. *Ecol. Monograph* 51:219-235.

[1] This bibliography includes (in chronological order) articles published in the open literature, based on studies conducted within the APCRP during the past 10 years (1980-1990).

Barko, J. W., and R. M. Smart. 1981b. Sediment-based nutrition of submersed freshwater macrophytes. *Aquat. Bot.* 10:339-352.

Barko, J. W. 1982a. Influence of potassium source (sediment vs. open water) and sediment composition on the growth and nutrition of a submersed freshwater macrophyte. *Aquat. Bot.* 12:157-172.

Barko, J. W. 1982b. Growth and morphology of submersed freshwater macrophytes in relation to light and temperature. *Can. J. Bot.* 60:877-887.

Barko, J. W. 1983. The growth of *Myriophyllum spicatum* L. in relation to selected characteristic of sediment and solution. *Aquat. Bot.* 15:91-10?.

Barko, J. W., and G. J. Filbin. 1983. Influences of light and temperature on chlorophyll composition in submersed macrophytes. *Aquat. Bot.* 15:249-255.

Barko, J. W., and R. M. Smart. 1983. Effects of organic matter additions to sediment on the growth of aquatic plants. *J. Ecol.* 71:161-175.

Filbin, G. J., and J. W. Barko. 1985. Growth and nutrition of submersed macrophytes in a eutrophic Wisconsin impoundment. *J. Freshwater Ecol.* 3:?75-286.

Smart, R. M., and J. W. Barko. 1985. Laboratory culture of submersed freshwater macrophytes on natural sediments. *Aquat. Bot.* 21:251-263.

Barko, J. W., and R. M. Smart. 1986a. Sediment composition: Effects on growth of submersed aquatic vegetation. Pages 72-78 in L. Anderson (ed)., Proceedings of International Symposium on watermilfoil (*Myriophyllum spicatum*) and related Halagoraceae species. Journal of Aqu. Plant Manage. Special Publication.

Barko, J. W., and R. M. Smart. 1986b. Sediment-related mechanisms of growth limitation in submersed macrophytes. *Ecology* 67:1328-1340.

Barko, J. W., M. S. Adams, and N. L. Clesceri. 1986. Environmental factors and their consideration in the management of submersed aquatic vegetation: A review. *J. Aquat. Plant Manage.* 42:1-10.

McFarland, D. G., and J. W. Barko. 1987. Interactive influences of temperature and sediment type on growth and morphology of *Hydrilla verticillata* (L.f.) Royle. *J. Freshwater Ecol.* 4:245-252.

Barko, J. W., R. M. Smart, D. G. McFarland, and R. L. Chen. 1988. Interrelationships between the growth of *Hydrilla verticillata* (L.f.) Royle and sediment nutrient availability. *Aquat. Bot.* 32:205-216.

Carter, V., J. W. Barko, G. L. Godshalk, and N. Rybicki. 1988. Effects of submersed macrophytes on water quality in the tidal Potomac River. *J. Freshwater Ecol.* 4:493-501.

Chen, R. L., and J. W. Barko. 1988. Effects of freshwater macrophytes on sediment chemistry. *J. Freshwater Ecol.* 4:279-289.

Lodge, D. M., J. W. Barko, D. Strayer, J. M. Melack, G. G. Mittelbach, R. W. Howarth, B. Menge, and J. E. Titus. 1988. Spatial heterogeneity and habitat interactions in lake communities. Pages 181-208 in S. R. Carpenter (ed.), *Complex Interactions in Lake Communities.* Springer-Verlag, New York.

Gunnison, D. G., and J. W. Barko. 1989. Rhizosphere ecology of rooted submersed macrophytes. *Water Res. Bull.* 25:193-201.

Stefan, H. G., G. M. Horsch, and J. W. Barko. 1989. A model for the estimation of convection exchange in the littoral region of a

shallow lake during cooling. *Hydrobiologia* 174:225-234.

Barko, J. W., D. Gunnison, and S. R. Carpenter. 1990. Sediment interactions with submersed macrophyte growth and community dynamics. *Aquatic Botany* (in press).

James, W. F., and J. W. Barko. 1990a. Estimation of phosphorus exchange between littoral and pelagic zones during nighttime convective circulation. *Limonology and Oceanography* (in press).

James, W. F., and J. W. Barko. 1990b. Factors affecting the zonation of sediment accretion rates and sediment composition in a north-temperate reservoir. *Archive fur Hydrobiol.* (in press).

Lillie, R. R., and J. W. Barko. 1990. Influence of sediment and groundwater on the distribution and biomass of *Myriophyllum spicatum* L. in Devil's Lake, Wisconsin. *J. Freshwater Ecol.* (in press).

McFarland, D. G., and J. W. Barko. 1990. Temperature and daylength effects on growth and tuber formation in hydrilla. *J. Aquat. Plant Manage.* 28:15-19.

Smith, C. S., and J. W. Barko. 1990. Ecology of Eurasian watermilfoil. *J. Aquat. Plant Manage.* 28:55-64.

Twilley, R. R., and J. W. Barko. 1990. The response of selected submersed macrophytes to experimental light and salinity conditions representative of estuarine conditions. *Estuaries* 13:311-321.

Population Dynamics of Submersed Macrophytes in the Tidal Potomac River

by
Virginia Carter,[1] *N. B. Rybicki,*[1] *and Michael Turtora*[1]

Introduction

Submersed macrophyte populations are very dynamic in terms of spatial variability and species composition. Both population declines and increases have been reported for the Chesapeake Bay and its tributaries, including the Potomac River (Bayley, Robin, and Southwick 1968; Orth and Moore 1984; Carter and Rybicki 1986). The historic distribution of submersed macrophytes in the tidal Potomac River illustrates this point.

Before the late 1930s there was an abundance of plants (Cumming, Purdy, and Ritter 1916; Secretary of the Treasury 1933); between the late 1930s and 1982, there were virtually no macrophytes in the tidal river (Carter, Paschal, and Bartow 1985); and in 1983 there was a resurgence of macrophytes (Carter and Rybicki 1986), followed by dramatic changes in population over the next 7 years.

Light availability has been identified as a major control on the distribution of submersed aquatic macrophytes in the Chesapeake Bay and the tidal Potomac River (Kemp et al. 1983, Carter and Rybicki 1990). Many factors (including total suspended solids (TSS), phytoplankton, epiphytes, nutrients, wind, and available sunshine) influence light availability, either directly or indirectly.

Light availability at depth is affected directly by the presence of TSS and phytoplankton in the water column and by epiphytes and sediment accumulations upon the leaf surface (Sand-Jensen and Sondergaard 1981, Kemp et al. 1983, Carter and Rybicki 1990). Increasing nutrient loading increases epiphytic algae and phytoplankton; the increases in phytoplankton cause an increase in TSS as well. Climatic factors such as wind and sunshine are also important (Orth and Moore 1986), although often disregarded when considering light availability.

The monoecious variety of the southeast Asian exotic *Hydrilla verticillata* (L.f.) Caspary became well established in the tidal river in 1983, following its discovery in 1982 (Steward et al. 1984). The changes in abundance of macrophytes in the tidal river from 1983-89 were caused primarily by fluctuations in the *H. verticillata* population. Although *Myriophyllum spicatum* L. and *Vallisneria americana* Michx. increased in abundance in the tidal river and spread downriver in advance of *H. verticillata*, they were generally replaced by *H. verticillata* in most areas <2 m in depth.

The tolerance of *H. verticillata* to low light levels and its ability to outcompete other species have been documented by numerous investigators (Van, Haller, and Bowes 1976; Bowes et al. 1977; Langeland and Sutton 1980; Sutton, Littell, and Langeland 1980; Spencer and Rejmanek 1990).

In discussing the resurgence of submersed macrophytes in the tidal Potomac River during 1983-85, Carter and Rybicki (1986) stated that several changes in water quality had occurred during or just prior to 1983. These included (1) a dramatic increase in Secchi depth to >0.80 m from <0.55 m, (2) a change in the primary nitrogen loading from ammonia to nitrate as a result of nitrification at the Blue Plains

[1] US Geological Survey, Reston, VA.

Waste Water Treatment Facility (BPF) in Washington, DC (Schultz 1989), and (3) a decrease in TSS and phosphorus loads from the BPF.

Because water clarity increased and nutrient loading declined, we did not attribute the resurgence to either factor alone, but suggested that there might be a synergistic effect. We did not consider climatic data in our analysis.

The purpose of this research was to examine the relations among water quality, climate, and submersed macrophyte population fluctuations in order to increase understanding of the mechanisms controlling population dynamics in the tidal Potomac River. Special emphasis was placed on *H. verticillata* because large changes in coverage were primarily the result of fluctuations in this species.

Study Site

The tidal Potomac River extends 61 km from Chain Bridge in Washington, DC, to Quantico, VA. The water is fresh (<0.5 mg/L dissolved solids) except during dry years with low river discharge. The average annual flow is 323 m^3 sec^{-1}. The river consists of a deep channel bordered by wide shallow margins or flats with several shallow tidal embayments on both the Virginia and Maryland sides.

For the purposes of this paper, the tidal river had been divided into two reaches, the upper tidal river from Chain Bridge to Marshall Hall, MD, and the lower tidal river from Marshall Hall to Quantico, VA.

Species reported from the tidal Potomac River prior to the late 1930s include *Vallisneria americana, Ceratophyllum demersum, Najas flexilis, Elodea canadensis,* and *Potamogeton crispus.* Thirteen species were reported from the tidal river from 1983-89. The most widespread species are *H. verticillata, V. americana, M. spicatum, C. demersum,* and *Heteranthera dubia*; the dominant species in terms of biomass and cover are *H. verticillata, M. spicatum,* and *V. americana.*

Methods and Materials

Several data sets were analyzed, including (1) climate data (wind speed, available sunshine) measured at National Airport (National Oceanic and Atmospheric Administration 1970-89); (2) water quality data (water temperature, Secchi depth, TSS, and chlorophyll-*a* concentration) collected by the Maryland Department of the Environment (MDE) and the District of Columbia Department of the Environment (DCE) and acquired through the Washington Metropolitan Council of Governments; and (3) water quality data collected by the US Geological Survey (USGS) between 1980 and 1989 (Blanchard, Coupe, and Woodward 1982; Coupe and Webb 1983; James et al. 1989). Collection methods for water quality data are summarized in Batiuk et al. (1991).

Because all the submersed macrophytes in the tidal Potomac River die back and undergo a period of dormancy, this analysis is limited to data from the growing season (April-October).

Because of differences in plant biomass and cover between the upper and lower tidal river, the data were analyzed by reach. MDE data were collected twice a month (once a month in 1983-84) at two stations in the upper tidal river and two stations in the lower tidal river. DCE data were collected once a month at a station in the upper tidal river. Data from those stations were combined for the upper and lower tidal reaches.

Growing-season means were calculated for Secchi depth, TSS, and chlorophyll-*a* concentration. For TSS, a few measurements were below the detection limit in 1983, 1984, and 1986; therefore, means were calculated for those years using log probability plotting (Helsel and Cohn 1988).

The USGS monitored the distribution of submersed macrophytes in the tidal Potomac River from 1983-89 (Carter et al. 1985; Rybicki et al. 1985, 1986, 1987; Rybicki, Anderson, and Carter 1988; Rybicki and

Schening 1990), supplying information on distribution and abundance to Dr. Robert Orth at the Virginia Institute of Marine Science (VIMS) for publication as part of the Chesapeake Bay Program (Orth et al. 1989). Aerial photographs of the submersed aquatic macrophytes have been digitized at VIMS, and distribution and abundance data are available through a centralized database maintained by the Chesapeake Bay Program.

For this report, information on coverage by submersed macrophytes in the upper and lower tidal river from 1984-89 (exclusive of 1988) was obtained from the database. Coverage in 1983 was estimated from USGS surveys; coverage in 1988 was estimated from the aerial photographs.

Meteorological data were in the form of monthly means for wind speed, percent available sunshine, and precipitation for the period 1970-89. A 20-year seasonal (April-October) mean was calculated for each parameter, and the seasonal means for the years of interest were compared with the long-term means.

The phenology of *H. verticillata* was taken into consideration in an analysis of the 1989 germination period climate and water quality data. Steward and Van (1987) showed that 70 to 80 percent of monoecious *H. verticillata* tubers germinated when the temperature was held at 15° C for 4 weeks. Examination of the 1989 temperature record gave the sampling date when the temperature became higher than 15° C and remained higher until the end of the summer.

The germination period was defined as the 6-week period including and immediately following that date, and the mean Secchi depth, TSS, and chlorophyll-*a* concentration were calculated by reach. For the meteorological data, the 2 months including and following the date when germination temperature was exceeded were selected, and the mean wind speed and percent available sunshine were calculated.

Because tuber size could be a factor in determining survival of newly germinated plants under poor water clarity conditions, we examined the relation of tuber size to sprout length in the laboratory. *Hydrilla verticillata* and *V. americana* tubers were collected from the tidal river during the winter dormant period. Samples of the smallest available and the largest available tubers were weighed and then sprouted in the dark at room temperature. The length of the sprouted plant was measured after 6 weeks (*H. verticillata*) and 9 weeks (*V. americana*) in the dark.

Results

Figure 1 shows the area covered by submersed macrophytes in the upper and lower tidal rivers from 1983-89. In 1983, the macrophyte population was a mixture of 13 species; propagules washed into the upper tidal river during the spring and summer became established in patches throughout the shallow areas. *Hydrilla verticillata* grew densely in the area surrounding Dyke Marsh, where several small plants had been discovered in 1982 (Steward et al. 1984). The plants expanded rapidly, reaching a total area of 1,300 ha in the upper tidal river from 1985-87.

Hydrilla verticillata dominated the upper tidal river by 1985 and composed more than 70 percent of the area covered by 1987. The 60-percent decrease in coverage in the upper tidal river in 1989 was primarily the result of loss of *H. verticillata*. Meanwhile, only small patches of submersed macrophytes became established in the upper end of the lower tidal river in 1985 and 1986; *Hydrilla verticillata* did not colonize this reach until 1986.

Submersed macrophytes had a dramatic expansion (350 percent) in coverage to 807 ha, dominated by *H. verticillata*, in 1989, coincident with the decline in the upper tidal river.

In 1983, when the plants returned, the upper tidal river had a mean seasonal Secchi

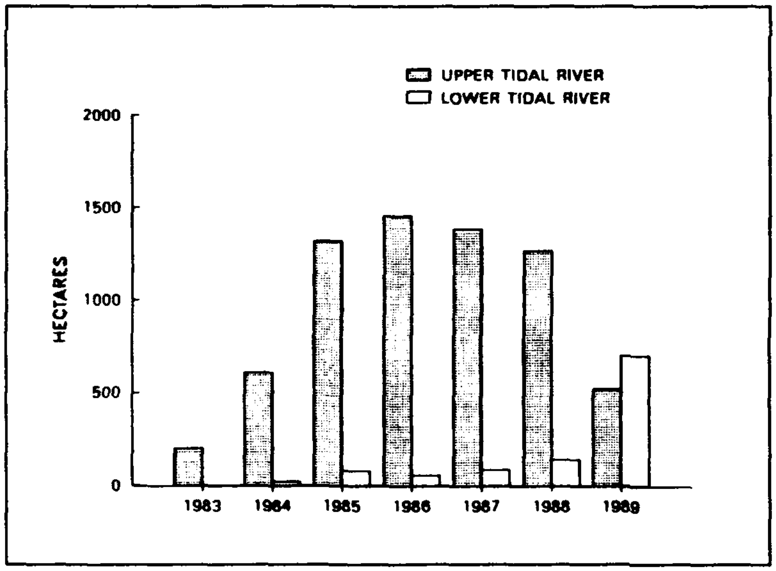


Figure 1. Hectares of submersed aquatic macrophytes in the upper and lower tidal Potomac River, 1983-89

in the upper tidal river, whereas mean seasonal TSS and chlorophyll-*a* concentration values were 23.0 mg/L and 32.8 µg/L, respectively, in the lower tidal river (Figures 3 and 4).

The available sunshine was 66 percent of that possible, significantly higher than the 20-year average of 60 percent (standard error = 0.45) (Figure 5a). Average wind speed was 11.1 km/hr, significantly lower than the 20-year average (mean = 14.2 km/hr, standard error = 0.32) (Figure 5b). The summer (June-August) wind speed was the lowest summer wind speed for the period of record (not shown).

depth of 0.77 m compared with 0.60 m in the lower tidal river (Figure 2). Mean seasonal TSS and chlorophyll-*a* concentration values were 18.8 mg/L and 15.2 µg/L, respectively,

From 1983 to 1989, conditions in the upper and lower tidal river gradually changed until the lower tidal river had greater water clarity than the upper tidal river (Figure 2). Seasonal mean Secchi depths in

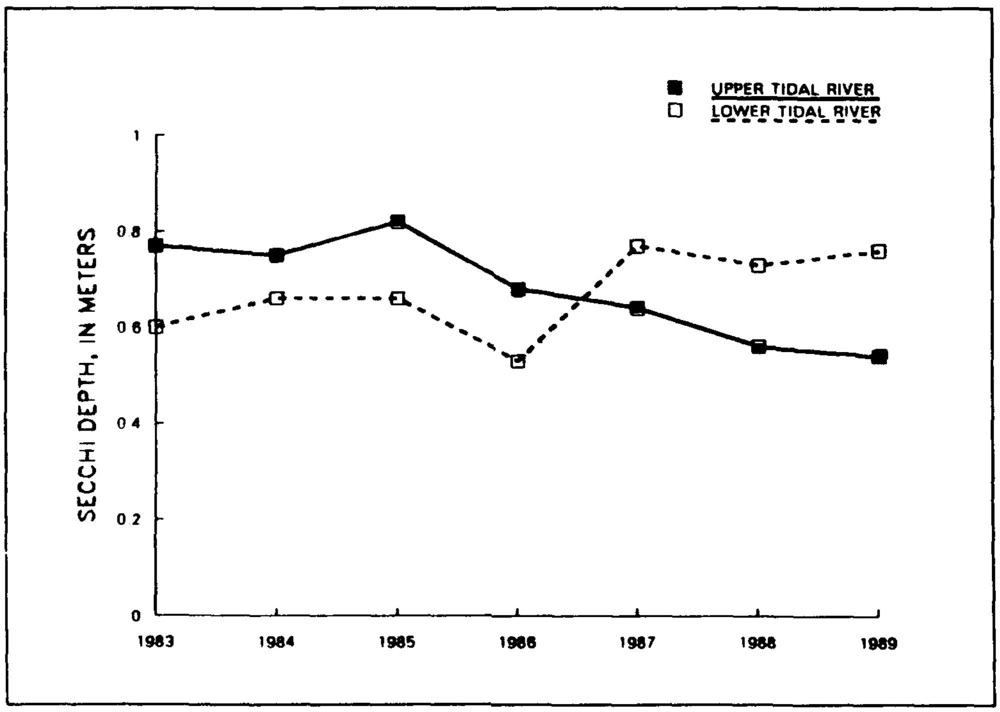


Figure 2. Seasonal mean (April-October) Secchi depth in the upper and lower tidal Potomac River, 1983-89

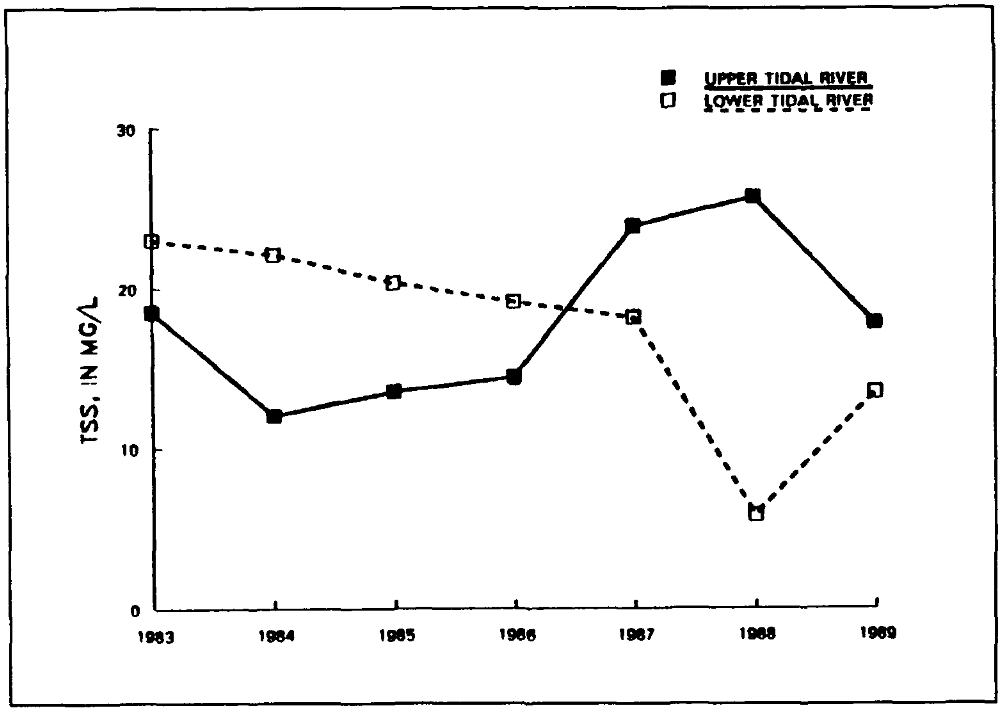


Figure 3. Seasonal mean (April-October) total suspended solids (TSS) in the upper and lower tidal Potomac River, 1983-89

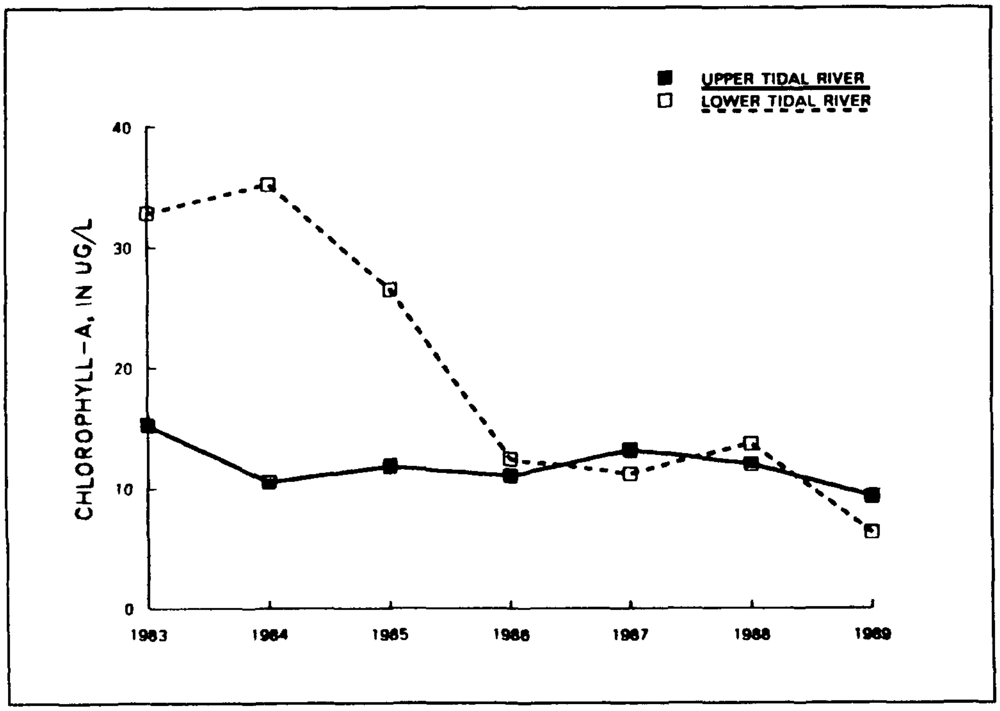
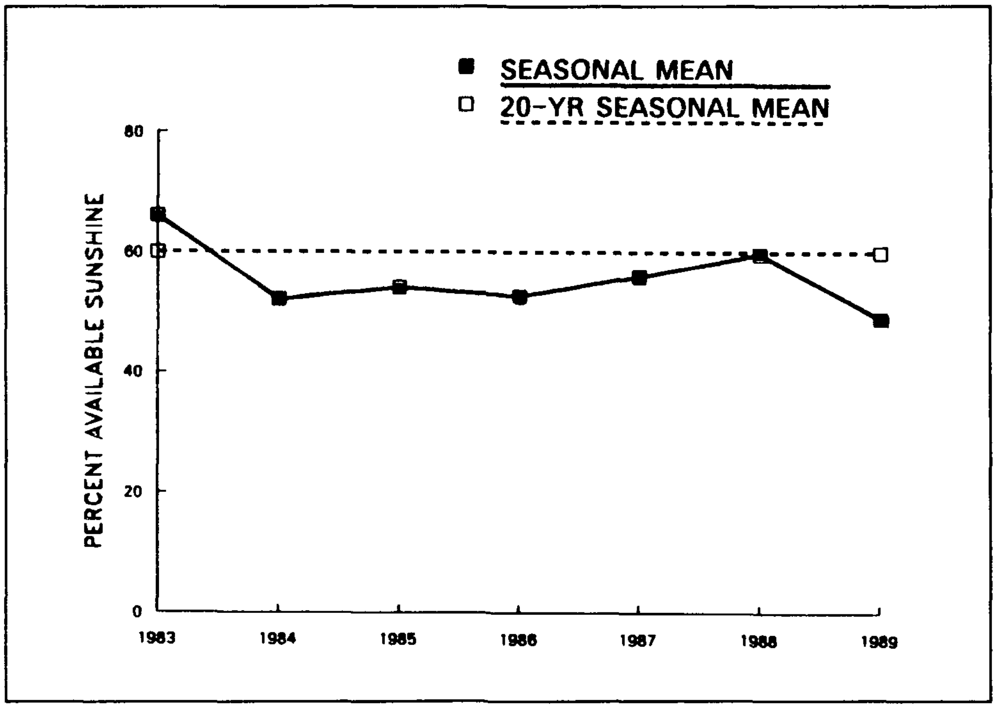
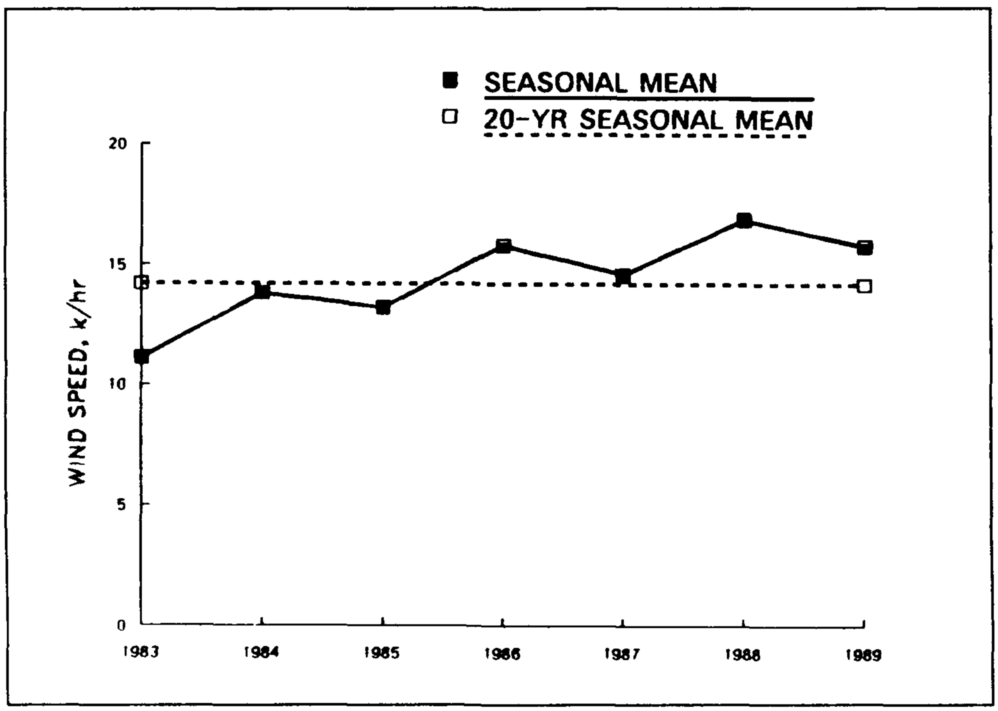


Figure 4. Seasonal mean (April-October) chlorophyll-a in the upper and lower tidal Potomac River, 1983-89



a. Percent available sunshine



b. Wind speed

Figure 5. Meteorological conditions in tidal Potomac River, 1983-89

the upper tidal river remained above 0.70 m through 1985 as the plants increased in abundance, and then dropped gradually to 0.54 m by 1989 (Figure 2). This decrease in Secchi depth was associated with an increase in mean seasonal TSS from ≤15 mg/L in 1984-86 to >18 mg/L in 1987-89. Mean seasonal chlorophyll-*a* concentration was <15 µg/L in 1984-89.

In the lower tidal river, mean seasonal Secchi depth remained between 0.49 and 0.66 m through 1986; relatively small numbers of plants were established in this reach. Secchi depth in the lower tidal river increased to 0.7 m during 1987-89, and macrophyte coverage increased. These changes in Secchi depth are associated with a gradual decrease in mean seasonal TSS from >20 mg/L in 1983-85 to <20 µg/L in 1986-89 and a large decrease in mean seasonal chlorophyll-*a* concentration from >25 µg/L in 1983-85 to <15 µg/L in 1984-1989.

In 1989, when the *H. verticillata* cover decreased by 60 percent in the upper tidal river and increased by 350 percent in the lower tidal river, the upper tidal river had a mean seasonal Secchi depth of 0.54 m, TSS of 17.7 mg/L, and chlorophyll-*a* concentration of 9.3 µg/L (Figures 2-4). The lower tidal river had a mean seasonal Secchi depth of 0.76 m, TSS of 13.4 mg/L, and chlorophyll-*a* concentration of 6.3 µg/L. The 1989 growing season was unusually cool and cloudy. The average wind speed was 15.8 km/hr, higher than the 20-year mean of 14.2 km/hr; the available sunshine was 49 percent, significantly lower than the 20-year mean of 60 percent (Figures 5a and 5b).

Figure 6 compares the water temperature for 1986, a year when *H. verticillata* was at a maximum coverage, and 1989, the year of the decline. In 1989, instead of gradually increasing temperature as in 1986, the mean water temperature rose from 13.7° C on April 17 to 18.8° C on May 2, and then decreased to 13.3° C on May 15, finally rising to 24.5° C on June 12. These biweekly values are in agreement with daily water temperature measured by the USGS. This means that

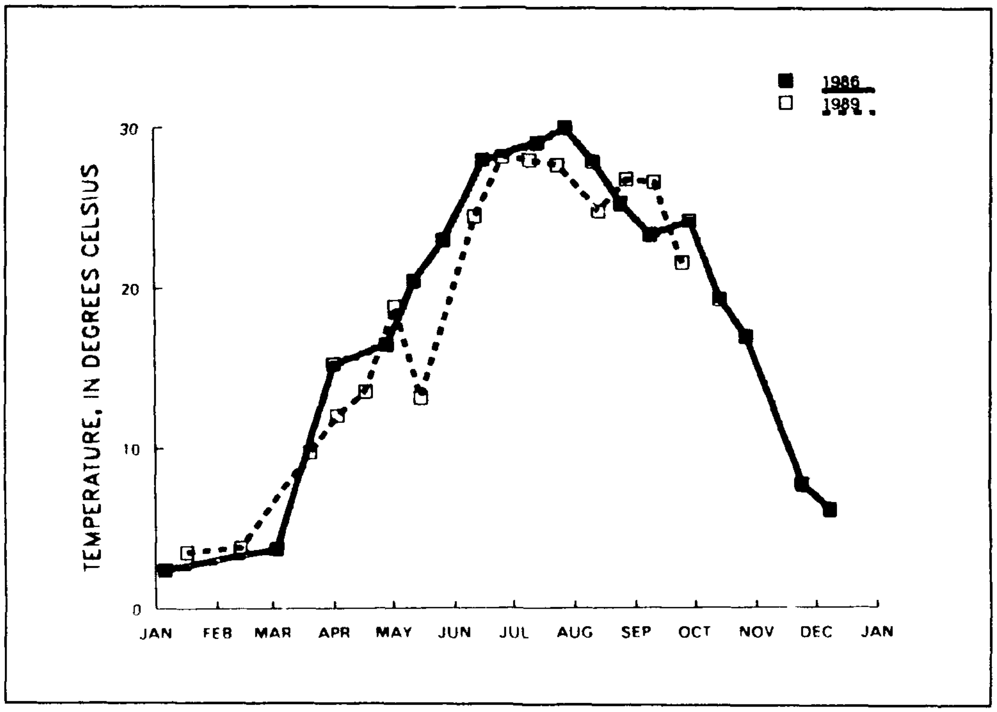


Figure 6. Water temperature in the tidal Potomac River, 1986 and 1989

H. verticillata germination was probably initiated in early May, but growth was slowed by low temperatures in late May.

Figure 7 shows the results of the germination period analysis. Mean germination period Secchi depth in the upper tidal river in 1989 was 0.47 m, lower than the seasonal average, whereas mean germination period Secchi depth in the lower tidal river was >0.88 m, higher than the seasonal mean. The low Secchi depth in the upper tidal river was associated with a germination period TSS of 18.0 mg/L and a chlorophyll-*a* concentration of 15.9 μg/L. The high Secchi depth in the lower tidal river was associated with mean TSS and chlorophyll-*a* concentrations of 10.8 mg/L and 4.6 μg/L, respectively, slightly lower than mean seasonal TSS and chlorophyll-*a* concentrations.

Table 1 shows the average weight of small and large *H. verticillata* and *V. americana* tubers and the average length of the plant at the end of the growth period. The smallest *V. americana* tubers weighed less than the largest *H. verticillata*. Leaf lengths from large tubers of *V. americana* were more than three times those from small tubers after 9 weeks; *H. verticilla* sprouts from large tubers were about three times longer than those from the smallest tubers.

With only 7 years of plant abundance data, there were too few data to attempt multiple regressions. Regressions of the change in plant area with the seasonal means of the three major parameters (Secchi depth, TSS, and chlorophyll-*a* concentration) showed that 82.7 percent of the variability could be accounted for by Secchi depth ($p = 0.004$) in the upper tidal river, whereas 55.0 percent of the variability in the lower tidal river was explained by TSS ($p = 0.056$).

Discussion

Our analysis suggests that submersed macrophytes returned to the upper tidal river in 1983 because of improved water clarity (Carter and Rybicki 1986) and a fortuitous combination of climatic factors affecting light availability. There was greater than normal percent available sunshine, and the low wind speed probably resulted in less sediment resuspension and turbulence.

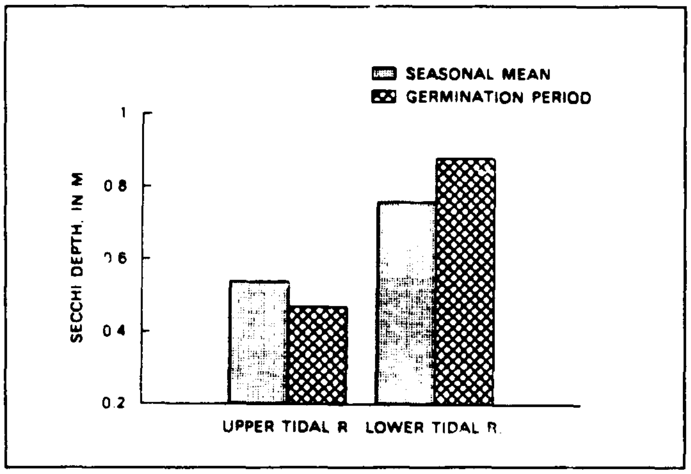
A phytoplankton bloom in the lower tidal river (Metropolitan Washington Council of Governments 1984, Woodward et al. 1984) spread into the upper tidal river after the plants had become well established and reached the water surface, causing a mean August-October chlorophyll-*a* concentration of 15.2 μg/L in the upper tidal river in 1983, but not affecting the newly established plants.

The data support the conclusion that the expansion of macrophyte populations in the upper tidal river and the spread of macrophytes into the lower tidal river after 1985 were the result of good water clarity (mean seasonal Secchi depths >0.7 m) associated with relatively low mean seasonal TSS (<20 mg/L) and chlorophyll-*a* (<15 μg/L) concentrations. Under these conditions, *H. verticillata* outcompeted all other species common to the

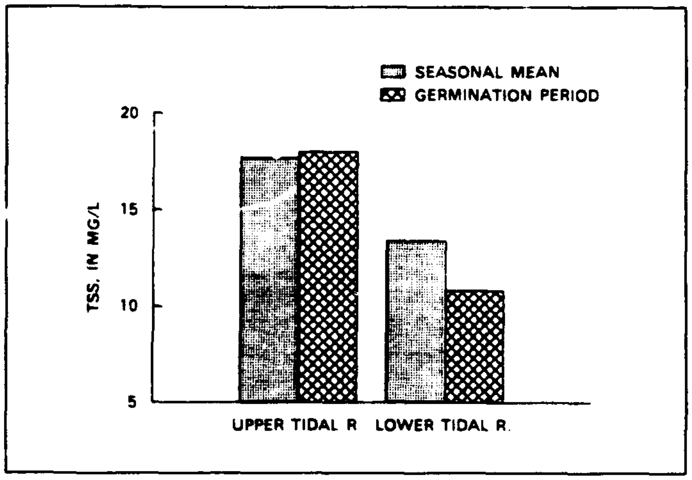
Table 1
Length of Plants Grown in the Dark from Large and Small Tubers

		Tuber Wet Mass, g			Plant Length, cm		
Species[1]	Tuber Size	N	Mean	SD	N	Mean	SD
H. verticillata	Small	8	0.0085	0.0026	7	2.7	0.7
	Large	8	0.1774	0.0400	8	7.8	3.4
V. americana	Small	5	0.1042	0.0191	5	16.0	8.7
	Large	5	0.4814	0.0526	5	52.0	10.8

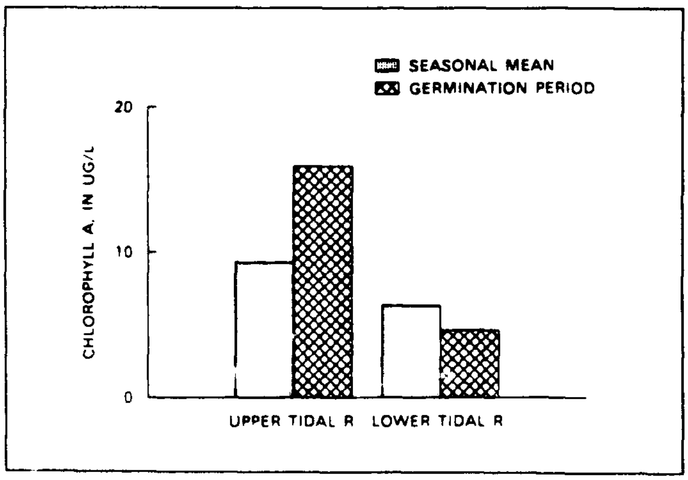
[1] Period of growth was 6 weeks for *H. verticillata* and 9 weeks for *V. americana*.



a. Secchi depth



b. Total suspended solids



c. Chlorophyll a

Figure 7. Seasonal germination period means for major plant growth parameters in the upper and lower tidal Potomac River in 1989

tidal river and rapidly covered all shallow areas in the main stem and tidal embayments.

When water clarity was <0.7 m, the balance between TSS and chlorophyll-*a* concentration was probably very important in determining plant distribution. If one or both of these parameters are high, there may be no increase in plant populations, and in fact, as illustrated by the 1989 upper tidal river data, populations may decrease dramatically.

Laboratory experiments have demonstrated that dioecious *H. verticillata* is well adapted to low light levels (Bowes et al. 1977; Van, Haller, and Bowes 1976). It has been shown to outcompete *V. americana* by virtue of its formation of a dense surface canopy that blocks light penetration (Haller and Sutton 1975). However, Barko and Smart (1981) reported that the monoecious *H. verticillata* elongated appreciably in light of 100 $\mu E\ m^{-2}\ sec^{-1}$, but apparently did not have sufficient organic reserves to form a canopy.

The sensitivity of *H. verticillata* to poor water clarity in the upper tidal river in 1989 was unexpected, especially because it appeared that *V. americana* and *M. spicatum* populations were relatively unaffected (personal observation, V. Carter and N. B. Rybicki).

The monoecious variety of *H. verticillata* adopts a prostrate form of growth, remaining in the lower half of the water column until about July, when it forms a dense surface canopy similar to that formed by dioecious *H. verticillata* (Carter et al. 1987). Based on the assumption that early growing season conditions were the key to the *H. verticillata* dieback in 1989, we looked critically at water temperature, tuber growth, and germination period water quality.

Submersed macrophyte populations overwinter in the form of propagules rich in stored carbohydrates—tubers, seeds, root masses and, in the case of *M. spicatum*, stems with active nodes. As rising spring water temperatures cause germination of these propagules, *V. americana* and *M. spicatum* grow rapidly toward the water surface into favorable light conditions. Growth of both *H. verticillata* and *V. americana* is relatively slow at low water temperatures (~12° to 16° C) (Barko and Smart 1981; Barko, Hardin, and Matthews 1982), whereas *M. spicatum* growth is not substantially slowed at these low temperatures (Barko and Smart 1981).

Vallisneria americana tubers are generally larger than those of *H. verticillata*, and our laboratory experiment suggests that they have more potential for elongation in the dark. *Hydrilla verticillata* tubers germinating in deep water (>1 m) may be at a disadvantage compared with *V. americana* when germination is initiated, and then water temperatures decrease or remain near the germination temperature for long periods of time. We hypothesize that *H. verticillata* tubers began to germinate in early May 1989, but growth was retarded because of temperatures <15° C.

Respiration exhausted much of the stored carbohydrate in the *H. verticillata* tubers by early June, and the poor light conditions in the upper tidal river caused the new plants to die before extending up into the water column. Light availability in the lower tidal river was better for growth in spite of the poor weather.

Bowes et al. (1977) found that tuber size positively influenced both shoot survival and shoot length of dioecious *H. verticillata* when tubers were germinated and held in complete darkness at 25° C. McFarland (1991) showed that small monoecious *H. verticillata* tubers showed less initial growth than large tubers when grown under identical greenhouse conditions.

Vallisneria americana, which is also tolerant of low light (Titus and Adams 1979), may also have had its growth retarded by the 1989 temperatures; however, with its larger tubers, it had sufficient energy to grow into an adequate light climate.

Myriophyllum spicatum, which generally germinates before all other plants in the river and reaches the surface within 3 weeks of the time that new sprouts are seen on the bottom (personal observation, V. Carter and N. B. Rybicki), did not appear to be affected.

References

Barko, J. W., Hardin, D. G., and Matthews, M. S. 1982. Growth and morphology of submersed freshwater macrophytes in relation to light and temperature. *Can. J. Botany* 60:877-887.

Barko, J. W., and Smart, R. M. 1981. Comparative influences of light and temperature on the growth and metabolism of submersed freshwater macrophytes. *Ecological Monographs* 51(2):221-235.

Batiuk, R., Heasly, P., Orth, R., Moore, K., Capelli, J., Stevenson, C., Dennison, W., Staver, L., Carter, V., Rybicki, N., Hickman, R. E., Kollar, S., and Bieber, S. 1991. Chesapeake Bay submerged aquatic vegetation habitat requirements and restoration goals technical synthesis. US Environmental Protection Agency CBP/TRS52/90 (in press).

Bayley, Sandra, Robin, H., and Southwick, C. H. 1968. Recent decline in the distribution and abundance of Eurasian milfoil in Chesapeake Bay, 1958-1975. *Estuaries. 1:73-84.*

Blanchard, S. F., Coupe, R. H., Jr., and Woodward, J. C. 1982. Water quality of the tidal Potomac River and estuary; Hydrologic data report, 1980 water year. US Geol. Surv. Open-File Rep. 82-152.

Bowes, G., Van, T. K., Garrard, L. A., and Haller, W. T. 1977. Adaptation to low light levels by *Hydrilla*. *J. Aq. Plant Management* 15:32-35.

Carter, V. and Rybicki, N. 1986. Resurgence of submersed aquatic macrophytes in the tidal Potomac River, Maryland, Virginia and the District of Columbia. *Estuaries* 9(4B):368-375.

Carter, V., and Rybicki, N. B. 1990. Light attenuation and submersed macrophyte distribution in the tidal Potomac River and Estuary. *Estuaries* 13:441-442.

Carter, V., Paschal, J. E., Jr., and Bartow, N. 1985. Distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and Estuary, Maryland and Virginia, May 1979 to November 1981. US Geol. Surv. Water-Supply Pap. 2234-A.

Carter, V., Rybicki, N. B., Anderson, R. T., Trombley, T. J., and Zynjuk, G. L. 1985. Data on the distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and transition zone of the Potomac Estuary, Maryland, Virginia and the District of Columbia, 1983 and 1984. US Geol. Surv. Open-File Rep. 85-82.

Carter, V., Rybicki, N. B., Jones, R. C., Barko, J. W., Dresler, P. V., Hickman, R. E., and Anderson, R. T. 1987. Data on physical, chemical and biological characteristics of *Hydrilla* beds, mixed vegetation beds, and unvegetated sites in the tidal Potomac River, Maryland and Virginia, 1987. US Geol. Surv. Open-File Rep. 88-709.

Coupe, R. H., Jr., and Webb, W. E. 1983. Supplement to water quality of the tidal Potomac River and estuary; Hydrologic data reports, 1979-1981 water years. US Geol. Surv. Open-File Rep. 84-132.

Cumming, H. S., Purdy, W. C., and Ritter, H. P. 1916. Investigations of the pollution and sanitary conditions of the Potomac watershed. Public Health Service Hygenic Laboratory Bulletin 104. US Treasury Dept.

Haller, W. T., and Sutton, D. L. 1975. Community structure and competition between *Hydrilla* and *Vallisneria*. *Hyacinth Control J.* 13:48-50.

Helsel, D., and Cohn, T. 1988. Estimation of descriptive statistics for multiple-censored water-quality data. *Water Resour. Res.* 24:1997-2004.

James, R. W., Jr., Simmons, R. H., Strain, B. F., and Smigaj, M. J. 1989. Water resources data, Maryland and Delaware, water year 1989; Vol 2, Monongahela and Potomac River Basins. US Geol. Surv. Water-Data Rep. MD-DE-89-2.

Kemp, W. M., Twilley, R. R., Stevenson, J. C., Boynton, W. R., and Means, J. C. 1983. The decline of submerged vascular plants in upper Chesapeake Bay: Summary of results concerning possible causes. *Marine Technology Society Journal* 17(2):78-89.

Langeland, K. A., and Sutton, D. L. 1980. Regrowth of *Hydrilla* from axillary buds. *J. Aquat. Plant Manage.* 18:27-29.

McFarland, D. G. 1991. See pp 103-109 in this proceedings.

Metropolitan Washington Council of Governments. 1984. Potomac River water quality, 1983. Washington, DC.

National Oceanic and Atmospheric Administration. 1970-89. Local climatological data. National Climate Center, Asheville, NC.

Orth, R. J., and Moore, K. A. 1984. Distribution and abundance of submerged aquatic vegetation in Chesapeake Bay: An historical perspective. *Estuaries* 7:531-540.

Orth, R. J., and Moore, K. A. 1986. Seasonal and year-to-year variations in the growth of *Zostera marina* L. (eelgrass) in the lower Chesapeake Bay. *Aq. Bot.* 24:335-341.

Orth, R. J., Frisch, A. A., Nowak, J. F., and Moore, K. A. 1989. Distribution of submerged aquatic vegetation in the Chesapeake Bay and tributaries and Chincoteague Bay - 1987. Chesapeake Bay Program, US Environmental Protection Agency.

Rybicki, N., and Schening, M. R. 1990. Data on the distribution of submersed aquatic vegetation in the tidal Potomac River and transition zone of the Potomac Estuary, Maryland, Virginia, and the District of Columbia, 1988. US Geol. Open-File Rep. 90-123.

Rybicki, N., Anderson, R. T., and Carter, V. 1988. Data on the distribution and abundance of submersed aquatic vegetation in the tidal Potomac Estuary, Maryland, Virginia and the District of Columbia, 1987. US Geol. Open-File Rep. 88-307.

Rybicki, N. B., Carter, V., Anderson, R. T., and Trombley, T. J. 1985. *Hydrilla verticillata* in the tidal Potomac River, Maryland, Virginia, and the District of Columbia, 1983 and 1984. US Geol. Surv. Open-File Rep. 85-77.

Rybicki N., Anderson, R. T., Shapiro, J. M., Jones, C. L., and Carter, V. 1986. Data on the distribution and abundance of submersed aquatic vegetation in the tidal Potomac River, Maryland, Virginia and the District of Columbia, 1985. US Geol. Surv. Open-File Rep. 86-126.

Rybicki, N. B., Anderson, R. T., Shapiro, J. M., Johnson, K. L., and Schulman, C. L. 1987. Data on the distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and Estuary, Maryland, Virginia and the District of Columbia, 1986. US Geol. Surv. Open-File Report 87-575.

Sand-Jensen, K., and Sondergaard, M. 1981. Phytoplankton and epiphyte development and their shading effect on submerged macrophytes in lakes of different nutrient status. *Int. Revue. Ges. Hydrobiol.* 66:529-552.

Secretary of the Treasury. 1933. Disposal of sewage in Potomac River: Senate

Document No. 172, 72nd Congress. Washington, DC.

Shultz, D. J. 1989. Nitrogen dynamics in the tidal freshwater Potomac River, Maryland and Virginia, water years 1979-81. US Geol. Surv. Water-Supply Pap. 2234-J.

Spencer, D. F., and Rejmanek, M. 1990. Propagule type influences competition between two submersed aquatic macrophytes. *Oecologia* 81:132-137.

Steward, K. K., and Van, T. K. 1987. Comparative studies of monoecious and dioecious hydrilla (*Hydrilla verticillata*) biotypes. *Weed Sci.* 35:204-210.

Steward K. K., Van, T. K., Carter, V., and Pieterse, A. H. 1984. Hydrilla invades Washington, D.C., and the Potomac. *Amer. J. Botany* 71(1):162-163.

Sutton, D. L., Littell, R. C., and Langeland. K. A. 1980. Intraspecific competition of *Hydrilla verticillata*. *Weed Science* 28:425-428.

Titus, J. E., and Adams, M. S. 1979. Coexistence and the comparative light relations of the submersed macrophytes *Myriophyllum spicatum* L. and *Vallisneria americana* Michx. *Oecologia* 40:273-286.

Van, T. K., Haller, W. T., and Bowes, G. 1976. Comparison of the photosynthetic characteristics of three submersed aquatic plants. *Plant Physiol.* 58:761-768.

Woodward, J. C., Manning, P. D., Schultz, D. J., and Andrle, W. S. 1984. Water quality and phytoplankton of the tidal Potomac River, August-November 1983. US Geol. Surv. Open-File Rep. 84-250.

Aquatic Plant Competition Studies

by
R. Michael Smart[1]

Introduction

Submersed aquatic plants comprise an important and beneficial component of many aquatic ecosystems. However, unchecked growth of weedy species can be detrimental, both to the aquatic life inhabiting the water body and to human users of water resources. The ultimate goal of aquatic plant management would be to promote the spread of aquatic plant communities having desirable attributes, while controlling the growth and distribution of weedy species. In pursuit of this goal, and in order to more effectively control the aquatic vegetation in Corps reservoirs and waterways, there is a need for information on the factors promoting or leading to submersed aquatic weed infestations.

If there are environmental factors that promote the spread of weedy species to the detriment of native, nonweedy species, these factors might be controlled or avoided, thus reducing the extent or magnitude of weed infestations. Since the distribution of weedy species may be limited by their environmental requirements, we have given considerable attention to studying the physiological responses of these species to their environment. The environmental factors we have considered include light, temperature, water chemistry, inorganic carbon supply, sediment composition, and sediment fertility.[2]

In our studies of common introduced and native species, we have found that most exhibit roughly similar environmental requirements, and respond similarly to different environmental conditions. Differences in individual species' preferences for particular environmental conditions thus do not, in themselves, seem sufficient to account for differences in the species composition of submersed aquatic plant communities. Therefore, the occurrence of weedy species in the aquatic environment cannot be directly ascribed to particular physical or chemical characteristics of the environment.

If there is not a set of environmental conditions that, in itself, leads to the development of weed infestations, it may be that the species composition of submersed aquatic plant communities is controlled by biotic (competitive) interactions among species. In other words, species composition of the community may be determined by the relative competitive abilities of the individual component species.

Since aquatic weed infestations often occur in areas that formerly supported native, nonweedy vegetation, it is commonly held that weedy species must be more competitive, outcompeting and eventually replacing the slower growing native vegetation. In spite of this widespread belief that weedy species are more competitive than nonweedy species, competitive displacement of native, nonweedy vegetation by introduced weedy species has never been unequivocally demonstrated.

A substantial body of literature on terrestrial plants indicates that weedy species are usually less directly competitive than nonweedy species. Terrestrial weedy species

---

[1] US Army Engineer Waterways Experiment Station, Lewisville Aquatic Ecosystem Research Facility, Lewisville, TX.

[2] J. W. Barko. 1986. Ecology of submersed macrophytes: A synopsis. Pages 35-38 in *Proceedings, 20th Annual Meeting, Aquatic Plant Control Research Program*, Miscellaneous Paper A-86-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

are, however, adapted for rapid colonization of new or disturbed environments, and it is this characteristic that contributes to their widespread distribution. In the absence of disturbance, more competitive, nonweedy species eventually outcompete the faster growing, but less competitive, weedy species in a fairly repeatable process known as ***succession***.

In view of the prevalence of the above scenario in the terrestrial environment, it is likely that similar processes occur in the aquatic environment. If plant succession in aquatic environments follows a pattern similar to that in terrestrial environments, we may eventually be able to identify methods that would accelerate the successional process, allowing managers to promote the establishment and persistence of native, nonweedy vegetation in order to slow the spread of weedy species.

To test several hypotheses on competition and succession in submersed aquatic plant communities, we have initiated short- and long-term studies at the Waterways Experiment Station (WES); at WES' Lewisville Aquatic Ecosystem Research Facility (LAERF), in Lewisville, TX; and, in cooperation with the Tennessee Valley Authority (TVA) at TVA's Murphy Hill Aquatic Research Facility near Guntersville Reservoir in northeast Alabama.

LAERF Study

The experimental objective of the pond study conducted at the LAERF was to determine the abilities of populations of the native species *Vallisneria americana* and *Potamogeton pectinatus* to resist invasion by *Hydrilla verticillata*. The experiment required observation of plant responses within permanent plots over an extended period. The plots were laid out as a series of hexagonal cells in a 1-acre pond (Figure 1). The sides of the cells were each about 2 meters long, and the area of the cell was 12 m^2, roughly approximating the area of a 4-m-diam circle.

The experiment included 96 cells, all of which were located below the 1-m depth contour in the pond. Species were assigned to cells in a regular pattern so that each species was surrounded by three cells of each of the other two species (Figure 1).

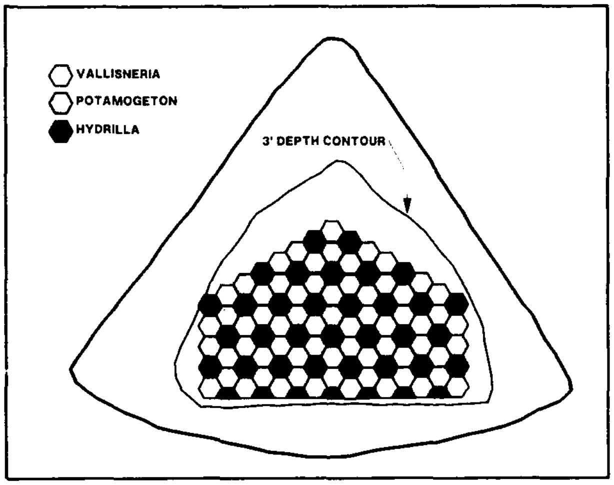


Figure 1. Experimental plot layout of pond study. Hexagonal cells are 2 m on each side with an area of 12 m^2

The sediment in every other cell of each species was fertilized with nitrogen (ammonium sulfate), which has been shown to potentially limit growth in these ponds. The entire pond bottom was rototilled prior to filling, to facilitate planting and to incorporate the nitrogen fertilizer. Plants of each of the species were planted in August 1990, by hand, on 30-cm centers as the pond was being filled.

During subsequent weeks we observed dense growth of two species endemic to the pond, *Najas guadalupensis* and *Chara vulgaris*. These two species, which grew from a seed/spore bank in the pond sediment, interferred with the establishment of *Vallisneria* and *Potamogeton*, thus complicating the analysis of experimental results. In October, after a 10-week period of growth, the pond was drained for observation and sampling.

Preliminary analysis indicates that *Hydrilla* grew very well, attaining full coverage in the cells where it had been planted, although it did not appreciably invade adjacent vegetated cells. These preliminary results indicate that preemptive establishment of native vegetation (in this case, through its seed/spore bank) can slow the spread of *Hydrilla.*

In the next phase of experimentation, the extant seed/spore bank will be eliminated prior to replanting the experiment. In the absence of preemptive competition from endemic annuals, we should be able to establish vigorous populations of *Vallisneria* and *Potamogeton* in the pond. Once these species are well established, we will reintroduce the weedy species (*Hydrilla)* and determine the ability of the natives to resist invasion.

Additional studies will examine the role of preemptive utilization of sediment nutrients as a factor enabling competitive species to resist invasion.

Guntersville Reservoir

One of the primary considerations in planning the Guntersville Reservoir research involved the release, by TVA, of large numbers of grass carp into the reservoir. The competitive species that we wished to experimentally evaluate (*Vallisneria americana* and *Potamogeton pectinatus*) are generally considered to be preferred food choices for the fish; also, the target species that we wished to replace, Eurasian watermilfoil (*Myriophyllum spicatum*), is one of the least favored foods. Thus, the presence of large numbers of grass carp would potentially interfere with a test of competition among these species in the reservoir.

We evaluated the use of exclosures or fences to exclude the carp from experimental plots, but decided against them as they would be expensive to construct, would require navigation permits that might result in costly delays, and might not be effective at excluding the grass carp. Since we were unable to conduct the research in Guntersville Reservoir, we elected to conduct the first year's trials in Stewart's Pond at Murphy Hill, immediately adjacent to the reservoir.

Prior to the start of the experiment, a 1-acre plot was laid out in the middle of a large expanse of monotypic Eurasian watermilfoil. This area was subsequently treated by TVA with a granular endothall formulation. The treatment produced excellent control, providing complete kill within the plot and leaving Eurasian watermilfoil intact all around the periphery of the plot.

The experimental objective was to determine the effects of benthic barrier and fertilizer application on the establishment and persistence of *Vallisneria* and *Potamogeton* in a water body dominated by Eurasian watermilfoil. We wished to test whether application of a benthic barrier surrounding the planting would increase the survival and competitive ability of the native species. We also felt that addition of fertilizer at planting might benefit the establishing plants.

The experimental design consisted of a factorial arrangement with two sediment treatments (barrier and no barrier), two fertility levels (control and fertilized sediments), three planting treatments (*Vallisneria, Potamogeton,* and unplanted controls), and included two harvest dates for evaluating results. The experiment was replicated four times for a total of 96 experimental units or subplots.

Each of the subplots consisted of a 1- by 1-m PVC pipe frame, held in place by attachment to the anchored benthic barrier or to a rope grid laid out on the bottom of the pond. A planting frame was constructed which divided the subplots into 36 cells approximately 15 by 15 cm. We then planted 36 bundles of approximately three to five *Vallisneria* plants or 36 sets of three *Potamogeton* tubers using the frame as a guide.

After a 5-week period we returned to evaluate the growth of the plants, and found that none had survived. Since no dead plants or

tubers were present, we suspected that the plants had been eaten. Subsequent observations and trapping suggested that the plants had been consumed by a large population of turtles residing in the pond. Since the turtles could be rather easily caught in turtle traps baited with *Vallisneria,* we elected to construct an exclosure in the pond, remove the turtles from within, and replant the barrier portion of the experiment.

Vallisneria was subsequently replanted in September 1990. *Potamogeton* tubers were unavailable at that time and will be replanted in the spring of 1991. The *Vallisneria* plots were evaluated in October 1990 and appeared to be successfully established. Eurasian watermilfoil was also beginning to reinvade the plots at that time. The plots will be monitored during 1991.

In addition to the pond site, two sites have been selected for study in Guntersville Reservoir. These sites, located in North Sauty Creek and Chisenhall Embayment, will be enclosed with a nylon-covered, galvanized fencing material to exclude grass carp from the plots. Experimental plots will be planted with *Vallisneria americana* and American pondweed (*Potamogeton nodosus*).

Growth of Black Bass in Different Densities of Hydrilla

by

James V. Morrow,[1] *K. Jack Killgore,*[1] *and Jan Jeffery Hoover*[1]

Introduction

The largemouth bass (*Micropterus salmoides*) is an important sportfish in southern reservoirs. This species frequents underwater cover, and is often associated with submersed aquatic macrophytes (Colle and Shireman 1980; Killgore, Morgan, and Rybicki 1989). Submersed aquatic macrophytes provide cover for young largemouth bass (Aggus and Elliott 1975) and are correlated with the abundance and recruitment of adult largemouth bass in reservoirs (Durocher, Procine, and Kraai 1984). Therefore, the relationship between largemouth bass and aquatic macrophytes should be considered when formulating an aquatic plant management plan.

Submersed aquatic macrophytes provide a substrate for invertebrates (Wiley et al. 1984), provide cover for other species of sunfishes such as bluegill (*Lepomis macrochirus*) and redear (*L. microlophus*), and improve water clarity (Engel 1987).

When submersed aquatic macrophytes become too dense, however, benefits to largemouth bass are negated by reduced foraging efficiency. As the density of aquatic macrophytes exceeds 50 stems/m^2, the predation success of largemouth bass declines rapidly, and is near zero at 250 to 1,000 stems/m^2 (Savino and Stein 1982). Wiley et al. (1984) found that maximum largemouth bass production occurred when macrophyte abundance was 53 g/m^3 (dry weight) and declined rapidly as macrophyte abundance increased.

Bluegills (*Lepomis macrochirus*) were also found to grow faster in areas of intermediate plant densities (111 stems/m^2) than in areas of low density (36 stems/m^2) or high density (177 stems/m^2) (Crowder and Cooper 1982). These studies suggest that largemouth bass grow best in areas of intermediate plant density.

The purpose of this study was to compare the growth of largemouth bass in ponds with three densities of hydrilla (*Hydrilla verticillata*) and to relate these findings to foraging and water quality differences between ponds. In addition, recommendations were developed for subsequent pond studies for the 1991 growing season.

Methods and Materials

This study was conducted at the Waterways Experiment Station's Lewisville Aquatic Plant Research Facility in Lewisville, TX. The study was conducted in two runs. The first run (midsummer, 9-25 August) had the following objectives: to determine the logistical requirements of the study, to determine the response of bass to the stresses of capture and stocking, and to examine the rate of depletion of the artificial forage base (i.e., bluegill). The second run was conducted in the early fall (13 September-25 October) and was terminated at the end of the plant growing season.

Three ponds, each measuring 42 by 89 m, were used in each run: no hydrilla (NH), intermediate hydrilla density (ID), and high hydrilla density (HD). Each pond was drained, tilled, and fertilized with ammonium sulfate at a rate of 540 kg/ha. Prior to flooding, the HD and ID ponds were planted with hydrilla sprigs 5 to 10 cm long. The bottoms of the HD ponds were planted with hydrilla sprigs spaced approximately 0.3 m apart, and

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

379 m^2 of each of the ID ponds was planted in ten 6.2- by 6.2-m blocks (Figure 1).

During the first run, each pond was divided along the long axis with a blocknet in an attempt to replicate within ponds. However, during fish harvest it was found that some fish moved through the net.

Prior to fish stocking, dissolved oxygen and surface temperature were measured, and epiphytic invertebrates were sampled with a sweep net. Six sweep net samples were taken in each pond (using a D-style dip net, 1-mm mesh), with the sweep made from the blocknet to the edge, perpendicular to the long axis of the pond.

Four hundred bluegills, 35 to 120 mm, were stocked into each pond 1 day prior to stocking bass. Ten black bass (*M. salmoides* and *M. punctulatus*) were stocked into each pond. Total length of each bass was measured to the nearest millimeter. Each bass was marked by fin clipping in the summer run or with anchor tags in the fall run.

At the completion of the runs, water temperature and dissolved oxygen were again measured, and plant biomass was estimated for each pond. Plant biomass was estimated by collecting twenty 0.5-m^2 samples and measuring the wet weight of each sample. Five biomass samples from each pond were dried in a kiln until all moisture was removed; the samples were then measured for dry weight.

Dry weight was regressed against wet weight, and this relationship was used to estimate the dry weight of the remaining samples. A randomized incomplete block design, with blocks being hydrilla samples or nonhydrilla samples, was used to determine difference in biomass between ponds.

Each pond was drained, and all the fish were collected. Bluegills were stored in isopropanol, for counting and measurement in the laboratory. Bass were again measured for length. The stomachs and sagittal otoliths were taken from each bass to determine feeding habits and age. Stomach contents were sorted by taxon, and individual food items were counted. Otolith sections were mounted as described by Porak, Coleman, and Crawford 1986).

Changes in length of each bass were determined by subtracting the length at the beginning of the runs from that at the end. A randomized incomplete block design, with age of the fish in years as the blocks, was

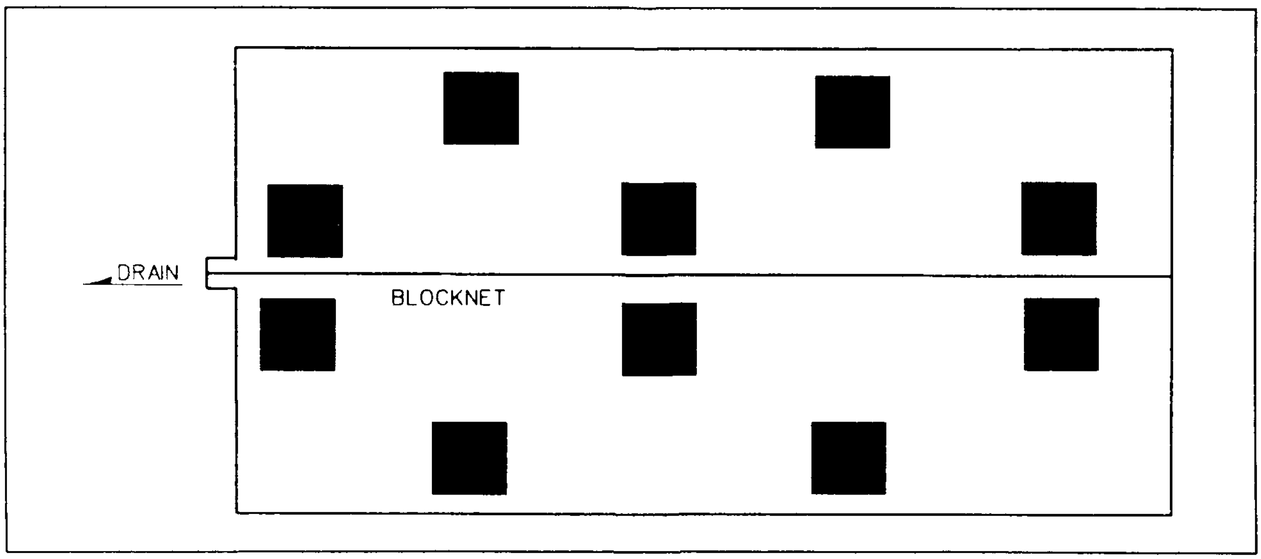


Figure 1. Schematic of experimental pond showing distribution of hydrilla (shaded areas) in intermediate-density pond

used to determine differences in growth between ponds. All tests of significance are at the $P = 0.05$ level.

Results

During both runs, hydrilla was at or near the surface of the water in the planted areas. The nonplanted areas of the ID and NH ponds had other aquatic plants (e.g., *Najas* sp. and *Chara* sp.) that contributed to biomass values. During the summer run, the biomass was similar between the NH and the ID ponds, primarily due to nonhydrilla plants (Table 1).

Table 1
Dry Weight Biomass of Aquatic Macrophytes in Experimental Ponds

Density	Dry Weight: Summer Run (g/m^2)	Dry Weight: Fall Run (g/m^2)
No hydrilla	182.4	62.4
Intermediate	205.2	280.0
High	336.4	328.8

Summer run:
Dry weight = 0.084 x Wet weight + 8.83, $R^2 = 0.85$, $n = 15$
Fall run:
Dry weight = 0.074 x Wet weight + 11.3, $R^2 = 0.96$, $n = 13$

Epiphytic invertebrates were abundant and qualitatively similar among ponds and sampling periods (Table 2). Total numbers were highest in the HD ponds.

Baetidae (small minnow mayflies) were present in all collections and were always abundant. Dragonfly nymphs (Libellulidae and Corduliidae) and damselfly nymphs (Coenagriidae) were abundant in all ponds planted with hydrilla; Libellulidae and Coenagriidae were most abundant in the HD ponds. Notonectidae (backswimmers) and Hydrophilidae (water scavenger beetles) were present in all collections but were only occasionally abundant.

Prey numbers in bass stomachs were low and were dominated by insects (Table 3). Dragonfly nymphs were the dominant food in all ponds, and Libellulidae were eaten in the largest numbers in the ID ponds. Baetidae and Notonectidae were eaten in low numbers, but no Hydrophilidae were found in the stomachs.

Table 2
Numbers of Invertebrates Collected in Six Sweep Net Samples Per Pond

Taxon	Summer NH	Summer ID	Summer HD	Fall NH	Fall ID	Fall HD
Ephemeroptera						
Baetidae	1,309	207	418	684	1,241	1,200
Caenidae	0	0	45	11	52	23
Odonata						
Libellulidae	7	310	1,007	1	600	1,097
Corduliidae	23	345	344	1	423	653
Coenagriidae	68	103	390	5	318	680
Hemiptera						
Notonectidae	240	13	84	16	58	39
Belostomatidae	0	7	8	0	8	6
Corixidae	0	2	17	19	1	7
Coleoptera						
Hydrophilidae LV[1]	5	18	4	3	5	3
Hydrophilidae AD[2]	7	9	30	14	6	7
Haliplidae LV	3	35	53	0	4	4
Dytiscidae LV	6	4	2	2	0	2
Dytiscidae AD	1	0	0	0	0	0
Diptera						
Chironomid	25	141	100	11	43	65
Total	1,694	1,194	2,502	767	2,759	3,786

[1] Larvae.
[2] Adults.

Bass grew in length an average of 8.3 mm during the 17 days of the summer run (Table 4). The NH pond bass showed significantly slower growth than the ID and the HD pond bass ($P \leq 0.05$), however, no difference could be detected between the ID and HD pond bass ($P > 0.05$). During the 45 days of the fall run, the bass grew in length an average of 24 mm. The ID pond bass showed significantly faster growth than bass from the NH and HD ponds ($P \leq 0.05$), with no significant difference detected between the NH and HD pond bass ($P > 0.05$).

Table 3
Mean Number of Food Items In Bass Stomachs In Each Pond

Taxon	Summer NH	Summer ID	Summer HD	Fall NH	Fall ID	Fall HD
Baetidae	0.0	0.0	0.0	0.2	0.0	0.1
Aeshnidae	0.0	0.0	0.0	0.9	0.2	0.5
Libellulidae	0.7	2.9	0.77	0.0	1.4	0.0
Zygoptera unidentified	0.0	0.0	0.0	0.1	0.0	0.0
Notonectidae	0.7	0.0	0.0	0.4	0.2	0.0
Corixidae	0.3	0.22	0.0	0.1	0.0	0.0
Belostomatidae	0.1	0.0	0.0	0.0	0.0	0.0
Haliplidae larvae	0.0	0.0	0.11	0.0	0.0	0.0
Fish	0.3	0.11	0.11	0.2	0.1	0.1
Astacidae	0.0	0.0	0.0	0.0	0.0	0.1
Unidentified insect	0.1	0.33	0.0	0.1	0.1	0.0

Table 4
Mean Change In Length of Black Bass, by Pond and Age Class

Age	Summer Run NH	Summer Run ID	Summer Run HD	Fall Run NH	Fall Run ID	Fall Run HD
0	—	—	—	—	2.0	—
1	10.0	6.0	17.0	31.0	34.2	28.6
2	1.0	6.0	2.5	23.0	—	18.0
3	5.0	11.5	8.3	16.5	—	12.5
4	—	10.5	—	—	5.0	18.0
Pond Mean	6.1[1]	12.0	9.9	23.1	28.1[2]	20.8

Note: All measurements are expressed in millimeters.
[1] Significantly less than change in length from intermediate- or high-density pond bass.
[2] Significantly greater than change in length from no-hydrilla or high-density pond bass.

Difference in growth due to age was significant in both runs. Using age classes as blocks decreased variability and helped to detect differences in growth between ponds.

Discussion

During the summer run, the bass from the ID and HD ponds showed significantly greater growth than bass from the NH pond. This difference could be due to several factors. First, high water temperature was prevalent in each pond. The surface temperature of all three ponds was 26° C at the start of the run and 33° to 34° C at the end. Coutant (1975) gives 27° C as an optimum temperature for largemouth bass, with growth nearing zero at 35.5° C.

In both the ID and HD ponds, the densest growth of hydrilla was in the deepest part of the pond near the drain (Figure 1). The canopy formed by the hydrilla inhibits sunlight, resulting in cooler temperatures in the ID and HD ponds. The NH pond had no plant canopy, and bass in this pond would not have had a thermal refuge.

The high temperatures and presence of aquatic plants had a synergetic effect with foraging technique. Largemouth bass search for forage at low plant densities but shift to ambush strategy as density increases (Savino and Stein 1982). Therefore, during periods of high water temperature, bass that actively search for prey will likely expend more energy and grow slower than bass that wait and ambush prey.

Another factor is availability of food. Libellulidae were more numerous in samples from the HD and ID ponds than in the NH ponds, and Libellulidae were the most common food items in bass stomachs from all ponds.

During the fall run, bass from the ID pond again showed the most growth; however, bass from the HD pond showed the least growth. In this run, temperatures in all three ponds varied from a high of 25° to 26° C at stocking to a low of 16° to 17° C at harvest, and should not have been a limiting factor.

The differences in growth may have been due to a combination of food availability and foraging efficiency. The HD and ID ponds again had higher numbers of preferred invertebrate food items, while the NH pond was again dominated by Baetidae. With lower

temperatures, the feeding of bass in the NH pond may have been more energetically efficient than feeding in the HD pond, where plants inhibit the fishes' search and capture efficiencies.

Results of this study indicate that black bass grow better, depending on water temperature and forage base, in environments characterized by intermediate to high plant densities and edge areas (sudden decreases in plant density) than in areas of uninterrupted high-density plants or areas with no plants. This is consistent with other studies that have shown aquatic plants to be important to the growth of fishes (Aggus and Elliott 1975, Wiley et al. 1984).

Recommendations for Future Studies

The following recommendations are made for future studies based on results of this study:

- Young-of-the-year largemouth bass will be used as the evaluation species for three reasons. First, variability in growth between age groups will be eliminated. Second, counting daily growth rings in juvenile fish is easier and more reliable than for adult fishes. Third, the addition of bluegill as a forage fish for largemouth bass will be eliminated, reducing the number of confounding variables that may affect fish growth. Invertebrates will be the only forage base for juvenile largemouth bass.

- Experimental treatments will consist of two to three plant species (e.g., hydrilla and pondweed), each planted at the same density. This will reduce the problems we experienced with maintaining desired plant levels in each pond. In addition, the experimental design will address an important management question of which types of plant species optimize the growth of fishes.

- Habitat and biotic variables monitored during the study will include water quality and invertebrate abundance.

- Replicates will be made concurrently in different ponds to eliminate the need of blocknets and to account for seasonal variation within treatments.

Acknowledgments

Assistance was provided by Kenneth Conley of Waterways Experiment Station; by Gary Dick, John Madsen, Becky Westover, Tammy Handcock, and Thomas Ussery of the Lewisville Aquatic Ecosystem Research Facility; and by James DeShaw and Carol Campbell of Sam Houston State University. Technical assistance was provided by Bruce Taubert of the Arizona Game and Fish Department.

References

Aggus, L. R., and Elliott, G. V. 1975. Effects of cover and food on year-class strength of largemouth bass. Pages 317-322 in R. H. Stroud and H. Clepper, eds. *Black Bass Biology and Management.* Sport Fishing Institute, Washington, DC.

Colle, D. E., and Shireman, J. V. 1980. Coefficients of condition for largemouth bass, bluegill, and redear sunfish in hydrilla-infested lakes. *Trans., Am. Fish. Soc.* 109:521-531.

Coutant, C. C. 1975. Responses of bass to natural and artificial temperature regimes. Pages 272-283 in R. H. Stroud and H. Clepper, eds. *Black Bass Biology and Management.* Sport Fishing Institute, Washington, DC.

Crowder, L. B., and Cooper, W. E. 1982. Habitat structural complexity and the interaction between bluegills and their prey. *Ecology* 63(6):1802-1813.

Durocher, P. P., Procine, W. C., and Kraai, J. E. 1984. Relationship between abundance of largemouth bass and submerged vegetation in Texas reservoirs. *North American Journal of Fisheries Management* 4:84-88.

Engel, S. 1987. The impact of submerged macrophytes on largemouth bass and bluegills. *Lake Reservoir Management* 3:227-234.

Killgore, K. J., Morgan, R. P., and Rybicki, N. B. 1989. Distribution and abundance of fishes associated with submersed aquatic plants in the Potomac River. *North American Journal of Fisheries Management* 9:101-111.

Porak, W., Coleman, W. S., and Crawford, S. 1986. Age, growth, and mortality of Florida largemouth bass utilizing otoliths. *Proc. Ann. Conf. Southeast. Assoc. Fish and Wildl. Agencies* 40:206-215.

Savino, J. F., and Stein, R. A. 1982. Predator-prey interaction between largemouth bass and bluegills as influenced by simulated, submersed vegetation. *Trans., American Fisheries Society* 111:255-266.

Wiley, M. J., Gorden, R. W., Waite, S. W. and Powless, T. 1984. The relationship between aquatic macrophytes and sport fish production in Illinois ponds: A simple model. *North American Journal of Fisheries Management* 4:111-119.

Habitat Value of *Potamogeton nodosus* in the Saline River

by

Andrew C. Miller[1] *and Edmond J. Bacon*[2]

Introduction

Background

Submersed macrophytes play a major role in biological and physical processes in lakes and rivers. Typically, macrophytes are more diverse and abundant in lentic habitats (standing waters) than in lotic systems (running waters); consequently, the majority of studies on submersed macrophytes have been conducted on ponds and lakes. Seddon (1972), Gregg and Rose (1982, 1985), McDermid and Naiman (1983), Pandit (1984), Carpenter and Lodge (1986), and Miller et al. (1989) have reviewed the potential impacts and habitat value of submersed macrophytes in a variety of habitats.

Studies in lakes have consistently shown that the presence of macrophytes increases invertebrate species diversity, density, and production (Watkins, Shireman, and Haller 1983; Engel 1985, 1988; Miller, Beckett, and Bacon 1989). However, studies in streams and rivers have shown more varied relationships between macrophytes and macroinvertebrates than in lake and reservoirs.

Minckley (1963) observed the highest invertebrate densities on the moss *Fissidens*, intermediate densities on submersed macrophytes, and the lowest invertebrate densities on substrates colonized only by diatoms and other algae. Harrod (1964) studied the invertebrate faunas associated with four species of macrophytes in a chalk stream and found that morphology, periphyton densities, chemical nature of the plant, and life histories of the colonizing animals were important variables in determining densities on macrophytes.

Pennak (1971) reported that invertebrate densities were 3 to 10 times higher in a stream with aquatic macrophytes than in a similar stream without macrophytes. In a study of an oligohaline section of the Hudson River, Menzie (1980) concluded that 16 to 35 percent of the invertebrate fauna inhabiting a cove area was found on *Myriophyllum spicatum* and that chironomids dominated. Rooke (1984) conducted a study of the Speed River, Ontario, and found that macroinvertebrates were higher on rock and cobble substrates than on any of the four species of macrophytes present. In a subsequent study of the macrofaunas in the Eramosa River, Rooke (1986) reported that the highest densities of invertebrates were found on two species of finely dissected aquatic macrophytes and a plastic imitation of *Elodea*.

Research on the habitat value of macrophytes

As part of the Aquatic Plant Control Research Program at the US Army Engineer Waterways Experiment Station, studies on the habitat value of aquatic plants for macroinvertebrates have been conducted in Arkansas, Mississippi, Louisiana, Florida, South Carolina, and Wisconsin. Studies have been designed to investigate the species composition and density of macroinvertebrates that depend directly and indirectly on submersed macrophytes.

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] Department of Natural Sciences, University of Arkansas at Monticello, Monticello, AR.

This paper summarizes results of studies conducted in the Saline River, Arkansas. Results of studies in other areas will be summarized in future proceedings of the APCRP; results of past studies have been described by Miller, Beckett, and Bacon (1989) and Miller, Bacon, and Beckett (1990).

Study Area

The Saline River is formed by the confluence of four second-order streams in western Garland County and flows approximately 207 km. The study site was located 5.8 km southwest of Rye, AR, at latitude 33°42′03″ and longitude 92°01′33″ on the Saline River in Bradley County, AR. This section of the river is classified as a third-order stream and is located 114 km below its source and 93 km above the confluence of the Saline River with the Ouachita River. Stream widths in the study area vary from 9.0 m to 23.2 m during June to August when discharge levels are below 150.0 cfs. A US Geological Survey (USGS) gaging station is located at the study site, and discharge levels have been recorded for calendar years 1987 and 1988 (Moore et al. 1989, 1990).

Two species of submersed aquatic macrophytes commonly occur in the lower Saline River. Small stands of curly pondweed *(Potamogeton nodosus)* occur sporadically in riffle areas, and scattered stands of water willow *(Dianthera americana)* occur marginally along all types of habitats except deep pools.

Study sites were randomly selected within three *Potamogeton nodosus* beds and adjacent riffle areas without aquatic vascular plants (no-plant zones). The sampling stations are designated as R-1, R-2, R-3, P-1, P-2, and P-3, with the designation R representing a riffle area without plants (no-plant zone) and the designation P representing a plant zone. The dimensions of the plant beds were as follows: P-1 (3.1 by 3.7 m); P-2 (7.3 by 11.0 m), and P-3 (3.7 by 7.3 m). The distance between P-1 and P-2 was 121.9 m, and the distance between P-2 and P-3 was 14.6 m.

The selection of three plant zones and three no-plant zones and the collection of five replicate samples from each area were specifically designed for statistical analysis by a three-way analysis of variance (ANOVA).

Methods

Samples of macroinvertebrates were collected at each station on 15 June 1988, 22 August 1988, and 2 November 1988. Riffle areas and plant beds were not accessible during the winter quarter because of high discharges. Physicochemical parameters including temperature, pH, dissolved oxygen, and specific conductance were measured at each collection site using a Solomat MPM 2000 monitoring system. Total alkalinity and total hardness were measured titrimetrically. Dissolved oxygen measurements were verified by the azide modification of the Winkler method. Current velocities were measured with a model 201B Marsh McBirney thermistor velocity meter.

Whole plant samples were collected by placing 60 to 200 cm of plant stems into a plastic bag. Collections of sediment samples and infaunal macroinvertebrates were made with a hand-held 9.8-cm coring device described by Miller and Bingham (1987). Five quantitative samples were collected under *Potamogeton* beds and from the nearest riffle area with similar velocity. Sediment samples were analyzed for particle size distribution and total organic content. Infaunal samples were screened in the laboratory with a No. 60 (250-µm mesh) US standard sieve and preserved with 10-percent formalin. Samples were stained with a rose bengal solution to facilitate separation of invertebrates.

Macroinvertebrates were removed by microscopical examination of all sediments at 15x magnifications. Organisms were stored in 70 percent ethanol. Slides of larval chironomids and oligochaetes were prepared for identification by the method described by Beckett and Lewis (1982). All organisms were identified to the lowest practical taxonomic level.

Macroinvertebrate densities found colonizing plant stems and leaves were expressed as numbers of organisms per gram of plant dry wet at 105° C. Macroinvertebrate species richness, species diversity, community composition, total density, and density of dominant taxa were calculated in accordance with the methods described by Brower and Zar (1984). Statistical analyses included a three-way ANOVA by the Statistical Analysis System, Duncan's Multiple Range, and nonparametric analyses.

Results and Discussion

Physical analysis

Typical current velocities in riffle areas without submersed aquatic plants were 0.51 m/sec at the surface and 0.33 m/sec near the substrate. In comparison, velocities within plant beds ranged from 0.40 to 0.50 m/sec above submersed plants and were reduced to 0.02 to 0.08 m/sec at the bottom. In most cases, current velocities were actually higher at the front edge of plant beds than in nearby riffles. Increased stream velocities immediately above submersed aquatic vascular plants have been described previously by Fonseca et al. (1982). These investigators reported that seagrass *Zostera marina* caused current velocities to be higher over the surface of submersed plants but substantially reduced inside the plant beds.

Fonseca et al. (1982) also noted that changes in current velocities per unit depth increased with increased plant abundances. This phenomenon was attributed to shoot bending, which accounted for a redirection of current flow and in-canopy reduction of current velocity. Gregg and Rose (1982) observed a similar trend in the Portneuf River in southeastern Idaho.

Discharge levels have been continuously monitored at the study site by a USGS gaging station. The data used for this study have been summarized in Moore et al. (1989, 1990). Discharge during 1987 ranged from a minimum of 9.9 cfs to a maximum of 67,000 cfs, with a mean rate of 2,281 cfs.

During 1988, discharges ranged from 21 cfs to 59,400 cfs, with an average discharge of 4,593 cfs. Typically during late summer and early fall, water levels are low with discharge levels usually less than 400 cfs with monthly mean rates less than 150 cfs. From June through August 1988, mean monthly discharges ranged from 123 to 130 cfs, and discharge levels on the three sampling dates were 15 June 1988 (112 cfs), 22 August 1988 (99 cfs), and 2 November 1988 (157 cfs).

Sediments were typically sandy gravel or gravelly sand with 60 to 70 percent of the particles consisting of pebbles, granules, and very coarse sand at most collection sites (Figure 1). Fine sand and very fine sand accounted for 20 percent or more of the total sediments at stations P-1 and P-3 located in the plant zones, whereas these finer sediments accounted for only 8 to 12 percent of all sediments at the other stations.

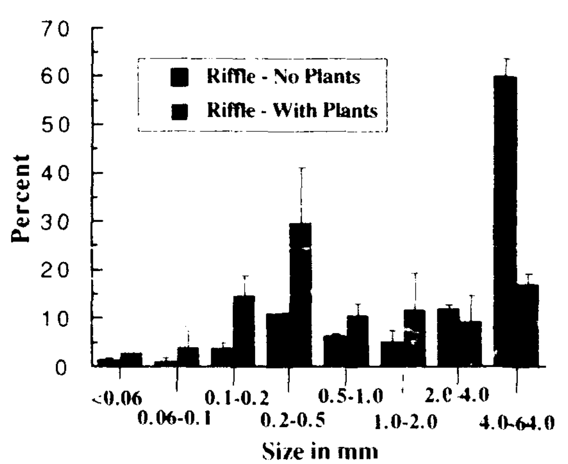


Figure 1. Grain size analysis of sediments collected in Saline River, 15 June 1988

The reduction in current velocities within plant beds increased the amounts of finer

sediments and organic matter. The percentages of organic matter were usually 3 to 6 times higher in sediments within plant beds. Gregg and Rose (1982) reported that macrophytes affected substrates by increasing the amounts of finer sediments and detritus.

Shallow-water areas were subjected to wide fluctuations in temperature, pH, and dissolved oxygen, in part due to the daily and seasonal variations in climate, photosynthetic activities, and breakdown of submersed macrophytes.

The following ranges in parameters were measured during three sampling dates: temperature (1.8° to 31.7° C); pH (6.1 to 7.2); dissolved oxygen (5.0 to 14.6 mg/L); discharge (9.9 to 67,000 cfs); specific conductance (52.5 to 530.0 µS); total alkalinity (7.0 to 44.0 mg/L); total hardness (13.0 to 94.0 mg/L); and turbidity (3.5 to 15.0 NTU). Stream discharge varied from 21 to 59,400 cfs and averaged 4,593 cfs during 1988. Discharge levels on the three sampling dates were 112 cfs (15 June 1988), 99 cfs (22 August 1988), and 157 cfs (2 November 1988).

Macroinvertebrates

Submersed stands of *Potamogeton nodosus* and riffle areas without aquatic vascular plants (no-plant zones) in the Saline River supported a diverse assemblage of macroinvertebrates, including 117 species dominated by dipterans (41 species), oligochaetes (14 species), clams (13 species), and trichopterans (10 species). Within the Order Diptera (two-winged insects), the family Chironomidae (midges) comprised 36 of the 41 species and accounted for 35 percent of the number of species and 80 to 90 percent of the total number of individuals occurring on *Potamogeton nodosus* and 30 to 80 percent of the total numbers of individuals occurring in areas without aquatic macrophytes.

Many midges occur in riffle areas and colonize submersed macrophytes during part of the year, whereas some species are entirely restricted to either riffle substrates or plant surfaces. These macroinvertebrate communities are discussed as phytophilous (plant-loving) species, which occur on the surfaces or burrow within aquatic vascular plants, and as benthic (bottom-dwelling) macroinvertebrates, which occur in no-plant zones.

Phytophilous macroinvertebrates

The number of taxa occurring on submersed *Potamogeton* varied from a low of 20 taxa on 15 June 1990 to a maximum of 33 taxa on 2 November 1988. Of the total 117 species occurring at the study site, only 33 taxa were collected in the quantitative sampling of plant stems and leaves. Macroinvertebrate population estimates on individual plants exhibited high variances. In most cases, the F-ratio indicated that the variances between different series of samples were significantly different ($P < 0.05$).

Chironomids were the dominant group of phytophilous macroinvertebrates, both in numbers of species and numbers of individuals per gram of dry mass of plants. Fifteen of the 33 taxa found on submersed macrophytes were chironomids, and the group accounted for 90.6 percent of all macroinvertebrates sampled.

Menzie (1980) reported that chironomids were the most abundant organisms on submersed macrophytes in the lower Hudson River. He observed that two different assemblages occurred, with one group residing primarily in the sediments and another living on the aquatic plants. Trichopterans (caddisflies) were the next most abundant group, but represented only 3.8 percent of the total density.

Average numbers of macroinvertebrates per gram of dry weight of plant biomass on 15 June 1988 varied from 565.8 individuals/g at station 2 to a maximum of 723.0 individuals/g at station 1. The mean for 15 samples collected on 15 June 1988 was 627.2, with dipterans accounting for 93.1 percent of the total.

Chironomids were the dominant species at all sampling stations. Individuals of *Rheotanytarsus exiguus* numbered 334.5 per gram and represented 59.1 percent of all macroinvertebrates and 64.5 percent of all chironomids occurring on *Potamogeton nodosus* at station 2. The next most abundant macroinvertebrates were *Polypedilum convictum, Thienemanniella xena,* and *Cricotopus bicinctus*. Mean numbers of macroinvertebrates per gram dry weight of *Potamogeton nodosus* at station 2 (which was similar to stations 1 and 3) are shown in Table 1.

On 22 August 1988, mean densities of macroinvertebrates varied from 340.3 to 579.4 individuals/g with an average of 472.3 individuals/g for all samples at the three sites. The highest densities occurred at stations 2 and 3 on 2 November 1988, at which time the average numbers per gram ranged from 1,369.8 to 1,780.7. The standing crop of macroinvertebrates at station 1 was only 262.2 individuals/g; this low density lowered the mean for the 2 November 1988 sampling to 1,138.3 individuals/g.

The reasons for the lower density at station 1 are not fully understood. Some possible explanations include fluctuating water levels, inhibition by more intense solar radiation, increased predation from fishes, and habitat disturbance from recreational activities. The depth of the *Potamogeton* bed at station 1 was considerably less than at the other stations, and it is possible that fluctuating water levels caused the plants to be partially or completely exposed for an unknown period.

Rheotanytarsus exiguus was the dominant chironomid on both the 15 June 1988 and 22 August 1988 sampling dates; however, on 2 November 1988 *Polypedilum convictum* was dominant, with 1,048.3 individuals/g. *Polypedilum convictum* accounted for 58.9 percent of macroinvertebrates on 2 November 1988, and *Cricotopus bicinctum* (with 389.4 individuals/g)

Table 1
Mean Numbers of Macroinvertebrates Per Gream of *Potamogeton nodosus* at Station 2, Saline River

Taxon	15 Jun 88	22 Aug 88	2 Nov 88
Hydra sp.	0.0	0.3	0.0
Macrostomum sp.	0.0	0.0	0.4
Tylenchus sp.	3.0	0.0	1.1
Dero nivea	0.0	0.0	2.8
Nais communis	6.7	0.3	18.3
Pristina leidyi	0.0	7.0	5.2
Pristinella osborni	0.0	0.0	0.4
Hydracarina	5.1	5.9	2.9
Baetis ephippiatus	0.0	11.8	0.8
Caenis hilaris	1.9	0.0	0.8
Tricorythodes atratus	0.0	15.0	0.6
Neoperla sp.	0.0	0.0	0.7
Taeniopteryx burksi	0.0	0.0	30.6
Cheumatopsyche sp.	3.6	8.9	9.8
Chimarra obscura	0.0	0.5	0.5
Brachycentrus sp.	3.3	0.2	0.3
Ceraclea sp.	0.0	0.0	0.4
Nectopsyche sp.	0.0	0.0	3.7
Hydroptila sp.	10.2	2.7	8.7
Oxyethira sp.	0.0	2.1	0.2
Leptocerus americanus	0.0	0.0	0.1
Acentria sp.	1.8	0.4	0.5
Petrophila sp.	0.0	2.5	0.8
Haliplus sp.	1.8	0.0	0.0
Stenelmis humerosa	9.9	2.9	0.1
Ablabesmyia parajanta	5.6	2.1	0.0
Labrundinia pilosella	0.0	2.1	0.0
Nilotanypus fimbriatus	0.0	1.4	0.0
Thienemannimyia sp.	5.6	0.0	7.0
Corynoneura celeripes	8.4	2.1	0.0
Cricotopus bicinctus	36.3	0.3	389.4
Thienemanniella fisca	5.6	0.7	1.7
Thienemanniella xena	50.2	9.8	48.6
Cryptochironomus fulvus	0.0	0.7	0.0
Polypedilum convictum	61.3	11.9	1,048.3
Polypedilum scalaenum	0.0	0.7	0.0
Tanytarsus cottmani	5.6	0.7	0.0
Tanytarsus glabrescens	0.0	0.0	8.7
Tanytarsus guerlus	0.0	0.7	0.0
Rheotanytarsus exiguus	334.5	242.7	166.9
Bezzia sp.	3.7	0.4	9.4
Simulium sp.	1.9	4.5	7.9
Diptera pupae	0.0	0.0	2.0
Total	566.0	341.3	1,779.6

comprised 21.9 percent of the total. The winter stonefly (*Taeniopteryx burksi*) was the fourth most abundant organism, with 1.7 percent of the total. The eggs of this species undergo diapause, and early instars typically appear in early to late fall.

Naidid oligochaetes were not as abundant in this lotic habitat as has been reported in some other studies. The most commonly occurring oligochaete was *Nais communis*, with 18.3 individuals/g and 1.0 percent of the total population on 2 November 1988.

Macroinvertebrate taxa that were collected only on *Potamogeton nodosus* included the lepidopterans *Acentria* sp. and *Petrophila* sp. and the caddisflies *Oxyethira* sp. and *Brachycentrus* sp. *Nectopsyche* sp. was predominantly found on submersed aquatic macrophytes and was most abundant on 2 November 1988. Berg (1949) reared 32 species of insects from *Potamogeton* and noted that *Potamogeton* spp. supported a large, heterogeneous fauna that were intimately or obligatorily related to living plants. McGaha (1952) expanded Berg's earlier study to include the relations of insects to 13 species of plants.

A one-way ANOVA and the nonparametric Kruskal-Wallis tests of significance indicated that phytophilous macroinvertebrate means or populations were significantly different ($P < 0.05$) for the three dates, but densities between sampling stations were not significant ($P > 0.05$) for all samples collected on the three dates.

Although the species richness was moderately high, the Shannon diversity indices were generally low. These values ranged from 1.9 on 2 November 1988 to 2.3 on 15 June 1988 because of the dominance of one species of chironomid, which represented 60 to 90 percent of the total number of individuals.

Benthic macroinvertebrates

The benthic areas in a zone without and with plants supported a diverse assemblage of 117 species of macroinvertebrates dominated by larval chironomids, oligochaetes, and clams. The mean numbers of organisms per square meter (individuals/sq m) in a no-plant and plant zone are summarized in Tables 2 and 3, respectively. As was the case in phytophilous samples, standard deviations were typically ≥50 percent of the sample densities.

Despite high sample variances, some definite seasonal trends and macroinvertebrate-plant associations were apparent. The mean density of macroinvertebrates from 45 samples collected in the plant zones was 49,030 individuals/sq m compared to a mean of 46,726 individuals/sq m in nearby riffle areas without macrophytes.

A three-way ANOVA indicated that the two population means were not significantly different ($P > 0.05$). A Duncan's Multiple Range Test of significance indicated that the sample means on 2 November 1988 in both plant and no-plant zones were significantly different ($P < 0.05$) from sample means collected on 15 June 1988 and 22 August 1988. Sample densities in riffle areas ranged from a low of 18,322 individuals/sq m at station R-2 on 22 August 1988 to a high of 87,155 individuals/sq m at station R-1 on 2 November 1988.

Dipterans accounted for 30 percent or more of the total numbers of individuals throughout the sampling duration but generally constituted more than 50 percent of the total. On 15 June 1988, dipterans contributed 70 to 82 percent of the total density in riffle areas; oligochaetes and pelecypods accounted for less than 10 percent of the total.

On 22 August 1988, dipterans constituted only 30 to 36 percent, while oligochaetes represented 10 to 16 percent and pelecypods comprised 26 to 38 percent of the total in the riffle samples. The Asiatic clam *Corbicula fluminea* represented more than 98 percent of the pelecypods in all samples. Dipterans were again dominant on 2 November 1988, and represented 49 to 59 percent of the total density.

Table 2
Mean Numbers of Benthic Macroinvertebrates per Square Meter in Riffle (No-Plant Zone) at Station 2, Saline River

Taxon	15 Jun 1988	22 Aug 1988	2 Nov 1988
Hydra sp.	27	0	0
Macrostomum sp.	0	0	398
Nematoda	159	159	530
Gordius sp.	27	0	0
Dero furcata	39	0	0
Dero nivea	670	201	5,093
Nais communis	0	0	375
Pristina leidyi	158	100	643
Pristina synclites	158	1,003	268
Pristinella jenkinae	0	0	54
Pristinella osborni	118	0	643
Stylaria lacustris	79	0	0
Branchiura sowerbyi	0	50	429
Tubificidae w/caps[1]	39	151	483
Tubificidae w/o caps[2]	197	351	1,823
Elimia sp.	0	0	53
Gyralus sp.	0	0	27
Physella sp.	27	0	0
Corbicula fluminea	2,015	6,867	15,431
Hydracarina	265	0	398
Baetisca lacustris	0	0	27
Baetis ephippiatus	345	106	0
Caenis hilaris	1,061	1,511	265
Leucrocuta hebe	212	106	27
Hexagenia limbata	0	27	0
Tricorythodes atratus	53	239	557
Ophiogomphus westfalli	0	159	27
Progomphus obscurus	27	0	0
Neoperla sp.	0	0	265
Perlinella drymo	265	0	27
Taeniopteryx burksi	0	0	292
Corydalus cornutus	27	0	0
Ceraclea sp.	424	106	1,140
Cheumatopsyche sp.	981	0	53
Chimarra obscura	1,220	0	0
Hydroptila sp.	106	133	902
Leptocerus americanus	0	0	27
Dineutus serrulatus	27	0	0
Peltodytes sexmanculatus	27	53	0
Stenelmis humerosa	928	1,459	3,420
Ablabesmyia parajanta	712	325	1,075
Labrundinia pilosella	596	0	144
Nilotanypus fimbriatus	293	0	71

[1] Immature and not identifiable, with capilliform chaeta.
[2] Immature and not identifiable, without capilliform chaeta.

(Continued)

Mean population densities in the riffle samples on 15 June 1988 and 22 August 1988 were 34,161 and 27,259, respectively, compared to 42,258 and 49,841 individuals/sq m in the plant zones. However, on 2 November 1988, the macroinvertebrate density was higher in the riffle areas (no-plant zones) than in the plant zone. The mean of 15 samples in riffle areas was 78,758 individuals/sq m compared to a mean of 54,992 individuals/sq m under the *Potamogeton* bed.

The reasons for this phenomenon are not fully understood, but it is likely that the high discharge levels during the winter, spring, and early summer, in combination with the highly unstable sandy gravel substrates, limit macroinvertebrate colonization in the riffle areas where current velocities are high.

The *Potamogeton* beds stabilize the substrate during these times of stress and provide food and shelter for macroinvertebrates. By the end of summer and early fall, discharge levels are typically below 100 cfs for an extended time period and allow substrates in riffle areas to stabilize. In addition, dense growths of diatoms and filamentous green algae dominated by *Spirogyra* develop during late summer and fall and provide an abundance of food for macroinvertebrates.

Sandy substrates are generally regarded as poor habitats, with low population densities and diversities (Hynes 1970). The sandy-gravel substrate in the Saline River is highly unstable during high-discharge periods, and the substrate composition and velocity are important controlling factors in the standing crop of macroinvertebrates.

Table 2 (Concluded)			
Taxon	**15 Jun 1988**	**22 Aug 1988**	**2 Nov 1988**
Procladius sublettei	0	195	3,010
Thienemannimyia sp.	2,575	325	108
Corynoneura celeripes	2,575	65	0
Corynoneura taris	0	0	108
Cricotopus bicinctus	532	65	3,655
Cricotopus tremulus	0	0	108
Orthocladius sp.	0	0	108
Nanocladius rectinervis	267	0	0
Synorthocladius semiverens	355	0	108
Thienemanniella xena	889	0	645
Cryptochironomus fulvus	1,421	1,039	1,935
Dicrotendipes neomodestus	0	0	860
Microtendipes sp.	0	65	215
Polypedilum convictum	3,996	390	4,623
Polypedilum scalaenum	7,370	519	1,183
Robackia demeijerei	799	0	108
Stictochironomus devinctus	712	455	108
Paratanytarsus sp.	267	1,169	968
Tanytarsus coffmani	90	0	0
Rheotanytarsus exiguus	346	65	2,150
Stempellinella sp.	1,154	390	4,300
Tanytarsus glabrescens	977	0	2,903
Tanytarsus guerlus	532	0	968
Bezzia sp.	875	477	2,917
Simulium sp.	27	0	0
Total	37,041	18,325	66,055

Mean population estimates ranged from a low of 25,720 individuals/sq m at station P-1 on 15 June 1988 to a maximum of 66,659 individuals/sq m at station P-1 on 2 November 1988. Mean densities for the sampling dates were as follows: 42,258 (15 June 1988), 49,841 (22 August 1988), and 54,992 (2 November 1988).

Some plant-macroinvertebrate associations were apparent in that the densities of nematodes, oligochaetes, and pelecypods were higher in benthic zones under *Potamogeton nodosus*. The densities of mayflies, stoneflies, and caddisflies were higher in the riffle areas or no-plant zones. Density of chironomids varied depending on habitat type, and appeared to be unrelated to presence of the plants (Figure 2).

Mean numbers of oligochaetes in the riffle and plant zone combined samples were 6,494 and 13,596 individuals/sq m, respectively (Figure 3). A one-way ANOVA test of significance indicated that the means were significantly different ($P < 0.01$), and a Kruskal-Wallis nonparametric

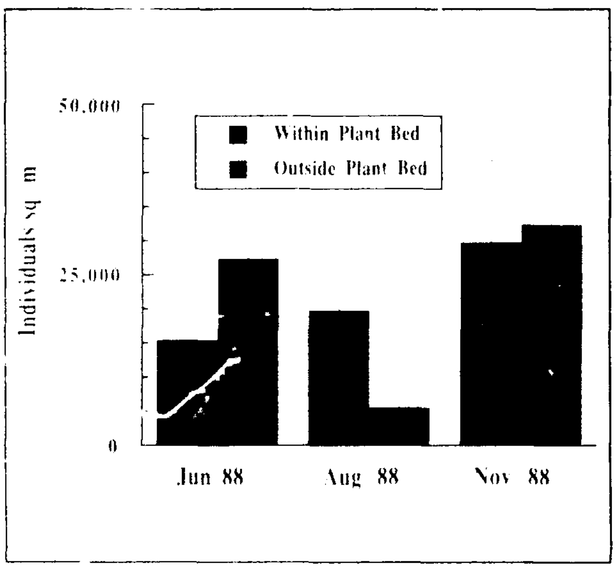


Figure 2. Distribution of larval chironomids in Saline River

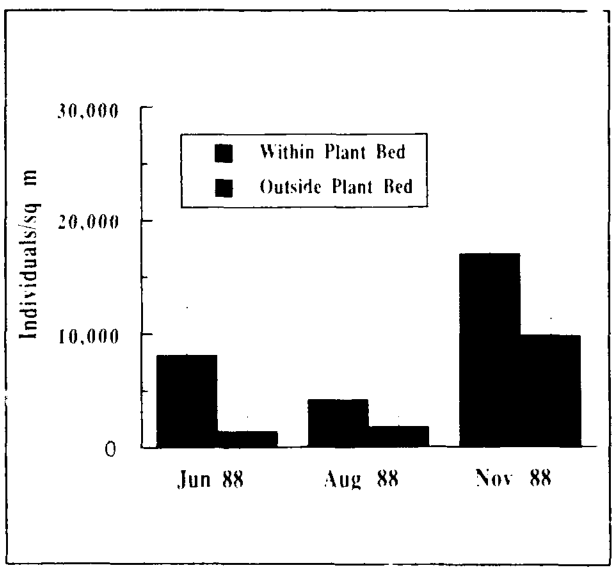


Figure 3. Distribution of oligochaetes in Saline River

Table 3
Mean Numbers of Benthic Macroinvertebrates per Square Meter under *Potamogeton nodosus* (P = Plant Zone) at Station 2, Saline River

Taxon	15 Jun 1988	22 Aug 1988	2 Nov 1988
Hydra sp.	0	0	0
Macrostomum sp.	27	0	106
Nematoda	424	504	689
Gordius sp.	0	0	0
Dero furcata	0	83	170
Dero nivea	5,837	3,165	3,735
Nais communis	0	0	170
Pristina leidyi	5,906	1,999	1,613
Pristina synclites	278	0	85
Pristinella jenkinae	0	0	0
Pristinella osborni	347	0	424
Stylaria lacustris	0	0	0
Aulodrilus piqueti	0	83	0
Branchiura sowerbyi	0	0	849
Ilyodrilus templetoni	0	0	85
Limnodrilus hoffmeisteri	0	0	170
Tubificidae w/caps	0	0	509
Tubificidae w/o caps	3,752	2,249	3,565
Ancylus sp.	0	0	53
Elimia sp.	0	27	0
Gyralus sp.	0	0	0
Physella sp.	0	0	0
Actionais ligamentina	27	0	27
Corbicula fluminea	3,553	17,235	8,591
Elliptio dilatata	80	0	27
Hydracarina	80	159	265
Baetisca lacustris	0	0	0
Baetis ephippiatus	0	106	0
Caenis hilaris	133	1,405	345
Leucrocuta hebe	27	133	0
Hexagenia limbata	0	80	0
Tricorythodes atratus	53	371	265
Argia translata	0	27	27
Ophiogomphus westfalli	53	53	27
Progomphus obscurus	0	0	27
Neoperla sp.	0	0	0
Perlinella drymo	27	0	0
Taeniopteryx burksi	0	0	106
Ceraclea sp.	80	504	451
Cheumatopsyche sp.	80	53	27
Chimarra obscura	27	53	0
Hydroptila sp.	186	53	371
Leptocerus americanus	27	0	27
Nectopsyche sp.	0	27	159
Dineutus serrulatus	0	0	0
Peltodytes sexmanculatus	27	0	0

(Continued)

test of significance indicated that the populations were significantly different ($P < 0.001$).

Although the sample means of pelecypods in the riffle samples and plant zone samples were 7,247 and 10,794, respectively, the means and populations were not significantly different ($P > 0.05$). Sample means and populations of other macroinvertebrates in the two zones were also not significant ($P > 0.05$).

Summary

Complex interactions of water and sediments with submersed macrophytes in flowing waters may significantly alter the physical environment by affecting current velocity, modifying sedimentation patterns and substrates, stabilizing or destabilizing habitat structures, modifying temperature regimes, and influencing available light. Macrophytes in lotic habitats have been reported to modify current flow patterns and to physically alter habitats to the extent that depositional patterns and accumulations of silt, sand, and particulate organic matter differed in areas with plants (Fonseca et al. 1982, Gregg and Rose 1982).

Aquatic plants in lotic systems have a measurable effect on physical conditions. In the Saline River the percentages of organic matter and fine-grained sediments were higher in the macrophyte beds than in the adjacent riffles. However, biotic differences did not always follow predictable patterns. Some macroinvertebrate species were entirely restricted to locations on or beneath submersed macrophytes, whereas others occurred only in riffle areas without macrophytes. Populations exhibited seasonal periodicity in response to variations in

Table 3 (Concluded)			
Taxon	15 Jun 1988	22 Aug 1988	2 Nov 1988
Stenelmis humerosa	159	2,678	1,830
Ablabesmyia mallochi	0	100	0
Ablabesmyia parajanta	227	100	224
Labrundinia pilosella	51	316	0
Nilotanypus fimbriatus	25	136	0
Procladius sublettei	76	201	672
Thienemannimyia sp.	303	954	75
Corynoneura celeripes	531	1,104	0
Corynoneura taris	0	0	0
Cricotopus bicinctus	0	100	1,569
Cricotopus tremulus	0	0	0
Orthocladius sp.	0	0	149
Nanocladius rectinervis	227	0	0
Parakiefferiella sp.	0	50	0
Synorthocladius semiverens	0	0	149
Thienemanniella fusca	0	0	75
Thienemanniella xena	152	151	822
Cryptochironomus fulvus	2,122	3,712	448
Dicrotendipes neomodestus	0	0	672
Microtendipes sp.	0	0	0
Polypedilum convictum	3,032	3,210	4,183
Polypedilum scalaenum	4,168	2,909	1,868
Robackia demeijerei	152	251	0
Stictochironomus devinctus	4,017	552	0
Paratanytarsus sp.	0	602	75
Stempellinella sp.	1,440	5,568	747
Tanytarsus coffmani	76	0	0
Rheotanytarsus exiguus	1,213	502	1,942
Tanytarsus glabrescens	76	50	1,643
Tanytarsus guerlus	834	301	224
Bezzia sp.	451	822	1,246
Simulium sp.	80	0	0
Diptera pupae	0	0	27
Total	40,443	52,821	41,605

temperature, available light, current velocities, available food, and biotic factors.

The most clear-cut beneficial effects of the plants were noted with the aquatic worms, or Oligochaeta. Densities of these organisms were always higher in vegetated rather than nonvegetated areas. Conversely, chironomid densities were variable and did not appear to be affected by presence of aquatic plants. The ability of these organisms to enter the drift and their areal mode of colonizing new habitats had a stronger influence on their distribution than did the substrate-stabilizing effects of macrophytes.

Acknowledgments

The authors would like to thank Penny Tinsley, Stephen Trundy, David Weaver, David Etheridge, James Hankins, and Stacy Wilson for their assistance in field collections and the tedious sorting of macroinvertebrates from benthic samples.

References

Beckett, D. M., and Lewis, P. A. 1982. An efficient procedure for slide mounting of larval chironomids. *Transactions of the American Microscopical Society* 101:96-99.

Berg, C. O. 1949. Limnological relations of insects to plants of the genus *Potamogeton*. *Transactions of the American Microscopical Society* 68:279-291.

Brower, J. E., and Zar, J. H. 1984. *Field and Laboratory Methods for General Ecology*, 2nd ed Wm. C. Brown Publishers, Dubuque, IA.

Carpenter, S. R., and Lodge, D. M. 1986. Effects of submersed macrophytes on ecosystem processes. *Aquatic Botany* 26:341-370.

Engel, S. 1985. Aquatic community interactions of submerged macrophytes. Technical Bulletin No. 156. Department of Natural Resources, Madison, WI.

Engel, S. 1988. The role and interactions of submersed macrophytes in a shallow Wisconsin lake. *Journal of Freshwater Ecology* 4:329-341.

Fonseca, M. S., Fisher, J. S., Zieman, J. C., and Thayer, G. W. 1982. Influence of the seagrass *Zostera marina* L. on current flow. *Estuarine, Coastal and Shelf Science* 15:351-364.

Gregg, W. W., and Rose, F. L. 1982. The effects of aquatic macrophytes on the stream microenvironment. *Aquatic Botany* 14:309-324.

Gregg, W. W., and Rose, F. L. 1985. Influences of aquatic macrophytes on invertebrate community structure, guild structure, and microdistribution in streams. *Hydrobiologia* 128:45-56.

Harrod, J. J. 1964. The distribution of invertebrates on submerged plants in a chalk stream. *Journal of Animal Ecology* 33:335-341.

Hynes, H. B. N. 1970. *The Ecology of Running Waters.* University of Toronto Press, Toronto, Canada.

McDermid, K. J., and Naiman, R. J. 1983. Macrophytes: Freshwater forests of lakes and rivers. *The American Biology Teacher* 45:144-150.

McGaha, Y. J. 1952. The limnological relations of insects to certain aquatic flowering plants. *Transactions of the American Microscopical Society* 71:335-381.

Menzie, C. A. 1980. The chironomid (Insecta: Diptera) and other fauna of a *Myriophyllum spicatum* L. plant bed in the lower Hudson River. *Estuaries* 3:38-54.

Miller, A. C., and Bingham, C. R. 1987. A hand-held benthic core sampler. *Journal of Freshwater Ecology* 4:77-81.

Miller, A. C., Bacon, E. J., and Beckett, D. C. 1990. The habitat value of aquatic macrophytes for macroinvertebrates—A comparison of lotic and lentic sites. Pages 198-211 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, A. C., Beckett, D. C., and Bacon, E. J. 1989. The habitat value of aquatic macrophytes for macroinvertebrates: Benthic studies in Eau Galle Reservoir, Wisconsin. Pages 190-201 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, A. C., Beckett, D. C., Way, C. M., and Bacon, E. J. 1989. The habitat value of aquatic macrophytes for macroinvertebrates. Technical Report A-89-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Minckley, W. L. 1963. The ecology of a spring stream, Doe Run, Meade County, Kentucky. *Wildlife Monographs* 11.

Moore, M. A., Porter, J. E., Westerfield, P. W., and Young, K. 1989. Water resources data, Arkansas water year 1988. Water-Data Report AR-88-1. US Geological Survey, Reston, VA.

Moore, M. A., Porter, J. E., Westerfield, P. W., and Young, K. 1990. Water resources data, Arkansas water year 1989. Water-Data Report AR-89-1. US Geological Survey, Reston, VA.

Pandit, A. K. 1984. Role of macrophytes in aquatic ecosystems and management of freshwater resources. *Journal of Environmental Management* 18:73-88.

Pennak, R. W. 1971. Toward a classification of lotic habitats. *Hydrobiologia* 38:321-334.

Rooke, J. B. 1984. The invertebrate fauna of four macrophytes in a lotic system. *Freshwater Biology* 1:507-513.

Rooke, R. B. 1986. Macroinvertebrates associated with macrophytes and plastic imitations in the Eramosa River, Ontario, Canada. *Archivio Hydrobiologia* 106:307-325.

Seddon, B. 1972. Aquatic macrophytes as limnological indicators. *Freshwater Biology* 2:107-130.

Watkins, C. E., Shireman, J. V., and Haller, W. T. 1983. The influence of aquatic vegetation upon zooplankton and benthic macroinvertebrates in Orange Lake, Florida. *Journal of Aquatic Plant Management* 21:78-83.

Phosphorus Exchange Between Littoral and Pelagic Zones During Nighttime Convective Circulation in Eau Galle Reservoir, Wisconsin

by
William F. James[1] *and John W. Barko*[1]

Introduction

Identification of internal and external phosphorus (P) sources to the epilimnion of lakes is fundamental to our understanding of eutrophication. Most investigations of internal P loading have focused on P release from anoxic, hypolimnetic sediments (e.g. Mortimer 1971; Theis and McCabe 1978; Nürnberg 1984, 1987; Riley and Prepas 1984; Nürnberg et al. 1986). Hypolimnetic P can be transported to the epilimnion via wind-driven mixing (e.g. Stauffer and Lee 1973; Kortmann et al. 1982; Stauffer and Armstrong 1984; Stauffer 1985, 1987; Effler et al. 1986) and/or *turbulent eddy diffusion* (e.g. Jassby and Powell 1975, Imboden and Emerson 1978, Robards and Ward 1978, Stefan and Hanson 1981, Wodka et al. 1983).

Horizontal P transport from the littoral zone to the pelagic epilimnion may be an important internal P loading mechanism as well (Prentki et al. 1979, Drake and Heaney 1987). While the littoral zone may serve as either a sink (Patterson and Brown 1979, Wetzel 1979) or a source of P (Barko and Smart 1980; Carpenter 1980; Landers 1982; Smith and Adams 1986), horizontal P transport has been difficult to quantify, due to inadequate information on hydraulic exchange between the littoral and pelagic zones. Two known mechanisms that potentially mediate horizontal P transport are wind-driven circulation (Weiler 1978) and convective circulation induced by nighttime cooling (Horsch and Stefan 1988; Stefan, Horsch, and Barko 1989).

Horsch and Stefan (1988) and Stefan, Horsch, and Barko (1989) showed that during calm, cold nights, littoral water cools more rapidly than pelagic water, due to volume differences, resulting in horizontal temperature gradients. Under these conditions, littoral water can move as an undercurrent below the warmer pelagic water, inducing a circulation pattern that transports P. Based on studies employing use of a fluorescent dye, we examined on two dates convective circulation patterns and P flux between the littoral and pelagic zones of Eau Galle Reservoir.

Methods

Eau Galle Reservoir is a small, dimictic, eutrophic US Army Corps of Engineers impoundment located in west-central Wisconsin (Figure 1). External P loading occurs primarily during spring and autumn, with most of the inflow (80 percent) occurring from the Eau Galle River. External P loading is usually minimal during summer stratification, although freshets do occur with some frequency (Kennedy 1987). Internal P loading usually dominates during summer stratification, with anoxic, profundal sediments accounting for much of this load (James, Kennedy, and Gaugush 1990; James, Barko, and Taylor, in press). Submersed littoral vegetation is extensive around the perimeter of the reservoir with dry mass densities reaching 500 g m^{-2} in some areas (Filbin and Barko 1985). *Ceratophyllum demersum* L. and *Potamogeton* spp. dominate the littoral assemblage.

---

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

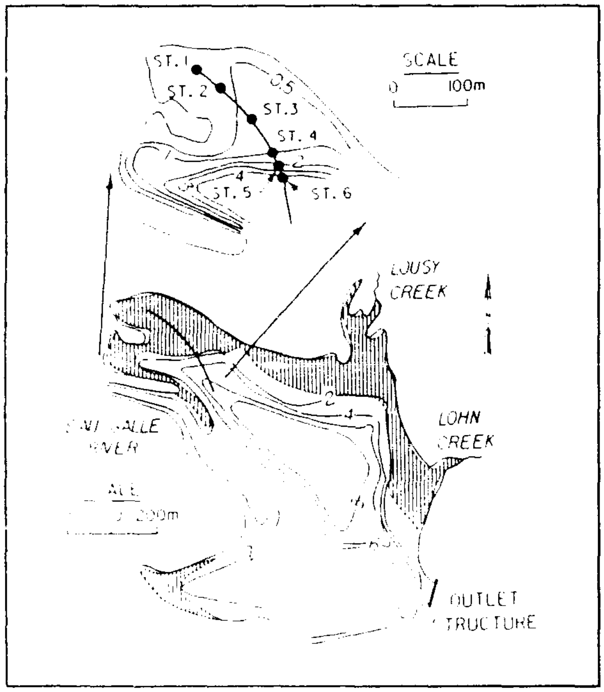


Figure 1. Morphometric contours (meters) of Eau Galle Reservoir and transect (heavy line) and station locations (solid circles) in the northwest bay. (Shaded area represents regions of macrophyte growth)

Two studies (25-26 July and 12-13 September 1988) were conducted in the northwest bay area of the reservoir to estimate hydraulic and P exchange between the littoral and pelagic zones during periods of nighttime convective cooling (Figure 1). Air temperature, wind speed, and wind direction (Omnidata International equipment) were monitored at hourly intervals at a station located 1 km from the study site.

A transect was established in the vegetated region of the bay, perpendicular to the slope of the basin, using posts driven into the sediment at approximately 25-m intervals. Buoys were placed in the deeper pelagic region at 10- to 20-m intervals to extend the transect into the open water. By attaching rope to the posts, boats could be pulled into the vegetated region with minimal disturbance to the water column. All stations and distances along the transect were surveyed using a transit.

Stations for water sampling in the littoral zone (st. 1-4, Figure 1) were located 165, 110, 55, and 0 m from the 1-m contour, while pelagic stations (st. 5 and 6) were located at the 2- and 4-m depth contours. All stations were monitored for temperature, dissolved oxygen, and pH at approximately 2000, 2400, 0400, 1000, and 1400 hr during each study. Stations 2-6 were sampled for P analyses at 2400 hr.

Temperature, dissolved oxygen, and pH were measured at 25-cm intervals at stations 1-4, and at 50-cm intervals at stations 5 and 6 with a Hydrolab Surveyor II. Dissolved oxygen was calibrated against Winkler determinations, and pH was calibrated using known pH buffer solutions (American Public Health Association (APHA) 1985). Samples for P analyses were collected with pneumatically driven close-interval syringe samplers (James, Kennedy, and Gaugush 1990). Each sampler consisted of a copper tubing manifold with syringes attached to ports located at 25-cm intervals. Samples were collected at these depth intervals from the surface to near the bottom (approximately 10 cm above the sediment-water interface) at the stations located in the littoral zone (st. 2-4) and at station 5. Samples were collected at these depth intervals at station 6 between the surface and 3-m depth in July, and between the surface and 4-m depth in September.

Samplers in the littoral zone were deployed on a stake and left undisturbed for 4 hr before collection to minimize the effects of any disturbances created during deployment. Total phosphorus (TP) was analyzed colorimetrically on a Technicon Autoanalyzer II after digestion with potassium persulfate (APHA 1985).

Rhodamine WT (Crompton and Knowles Corporation, USA), a red fluorescent dye, was placed in the littoral zone near the edge of the macrophyte bed (i.e., littoral-pelagic interface; Figure 1) at 2100 hr during each study to examine hydraulic exchange during the nighttime cooling period. The dye was placed in this location to observe both forward

(i.e., into the pelagic zone) and reverse (i.e., into the littoral zone) movement. Dye (300 ml) (2.4 g L^{-1}) was thoroughly mixed with approximately 100 L of lake water collected uniformly with a pump and hose from all depths of the 1-m deep station. The dye mixture was then pumped back into the water column at all depths by continuously moving the hose up and down. Initial concentration measurements indicated that the dye was evenly distributed in the water column at 500 to 1,000 $\mu g\ L^{-1}$.

Dye movement from the injection location was tracked with a Turner Designs Fluorometer (model No. 10-005R) calibrated with known Rhodamine WT dye standards, ranging from 0.48 to 480 $\mu g\ L^{-1}$. Untreated lake water typically had a background fluorescence of 0.2 $\mu g\ L^{-1}$. The detection limit for dye concentration was arbitrarily set at 0.5 $\mu g\ L^{-1}$ from a comparison of a 0.48-$\mu g\ L^{-1}$ dye standard and untreated lake water measurements.

The forward and reverse leading edges of the dye cloud were tracked at 2- to 4-hr intervals for 20 to 24 hr after injection. To find these leading edges, fluorometric measurements were taken at 0.10- to 0.25-m depth intervals and 5- to 10-m horizontal intervals along the rope transect in the littoral zone and at buoyed stations in the pelagic zone. These edges were located to within ±5 m. In addition, measurements were made at lateral stations, although less frequently, to track movement relative to the slope of the basin.

Forward and reverse flow velocities (m sec^{-1}) were calculated as the distance of the leading edges of the dye cloud from the initial injection point divided by time. Use of the edges of the dye cloud in the calculation reflected maximal velocities. Forward and reverse volumetric flow rates ($m^3\ hr^{-1}$) through the littoral-pelagic interface were estimated for the entire reservoir as the product of flow velocity, vertical expanse of the dye cloud leading edges, and horizontal length of the littoral-pelagic interface divided by time. The littoral-pelagic interface length was equivalent to the lateral distance of the outer edge of the macrophyte beds around the reservoir (about 1,000 m; see Figure 1). Here, we assumed that dye movement and, therefore, flow velocities were similar along the entire length of the littoral-pelagic interface.

Total phosphorus exchange rates (g hr^{-1}) into the pelagic zone were calculated as the product of forward volumetric flow rates and horizontal and depth-weighted TP concentrations obtained from stations 2-4. The TP exchange into the littoral zone was calculated similarly as the product of reverse volumetric flow rates and weighted concentrations obtained from stations 5 and 6. TP concentrations were weighted horizontally with respect to length between stations along the transect.

Areal daily TP exchanges (mg $m^{-2}\ day^{-1}$) into and out of the littoral zone were calculated as the product of TP exchange and the time period of daily maximal convective circulation divided by the reservoir's surface area (0.6 km^2). Net areal daily TP flux was calculated as the difference between littoral and pelagic areal daily TP exchange.

Results

Temperatures dropped substantially during the nights of both study periods (Figure 2). Wind speed decreased to near zero between 2100 hr on 25 July and 0900 hr on 26 July, then increased during the day of 26 July from a southerly direction. During the September study period, wind speed declined to near zero between 0200 hr and 0900 hr on 13 September, then increased from a northerly direction during that day.

At 2000 hr on 25 July, the littoral zone was stratified with warmer surface temperatures than those of the pelagic zone (Figure 3). During nighttime cooling on this date, littoral stratification was disrupted, and the entire epilimnion cooled to about 24° C by 2400 hr. The littoral zone cooled further by 0400 hr on 26 July, resulting in marked horizontal temperature gradients. By 1000 hr on 26 July, intrusion of cooler water from the littoral

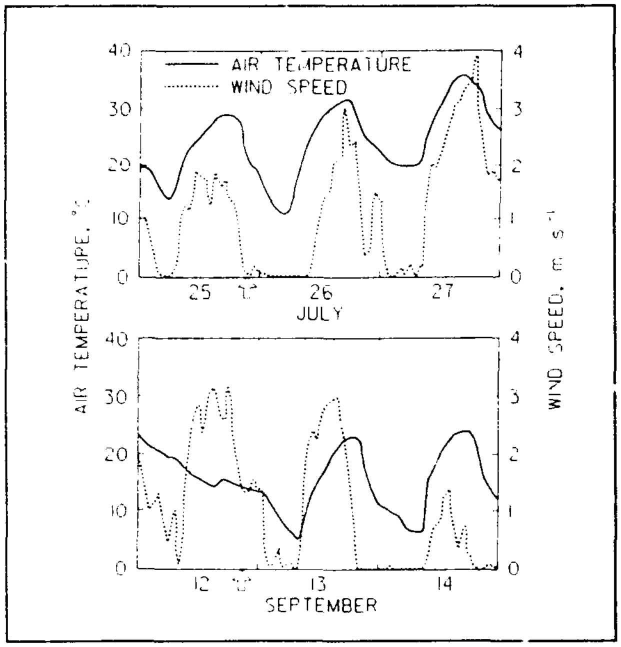


Figure 2. Hourly variations in air temperature and wind speed during 25-27 July and 12-14 September 1988. (Arrow represents the time of dye injection)

zone occurred between the 1- and 3-m depths of the pelagic zone (Figure 3). The littoral zone was again stratified by 1400 hr on 26 July, and exhibited warmer surface temperatures than those of the pelagic zone.

In contrast, cooler autumnal weather generated lower water column temperatures in September. During the September study period, water temperatures were nearly uniform at 1930 hr on 12 September (Figure 4). However, nighttime cooling established horizontal temperature gradients between the littoral and pelagic zones by 0500 hr on 13 September. Daytime warming again generated nearly uniform water temperatures by 1000 hr on 13 September. Littoral surface water warmed further than that of the pelagic zone by 1400 hr on this date.

During both study periods, the dye cloud moved as a bottom current from the littoral to the pelagic zone (Figure 5). Although

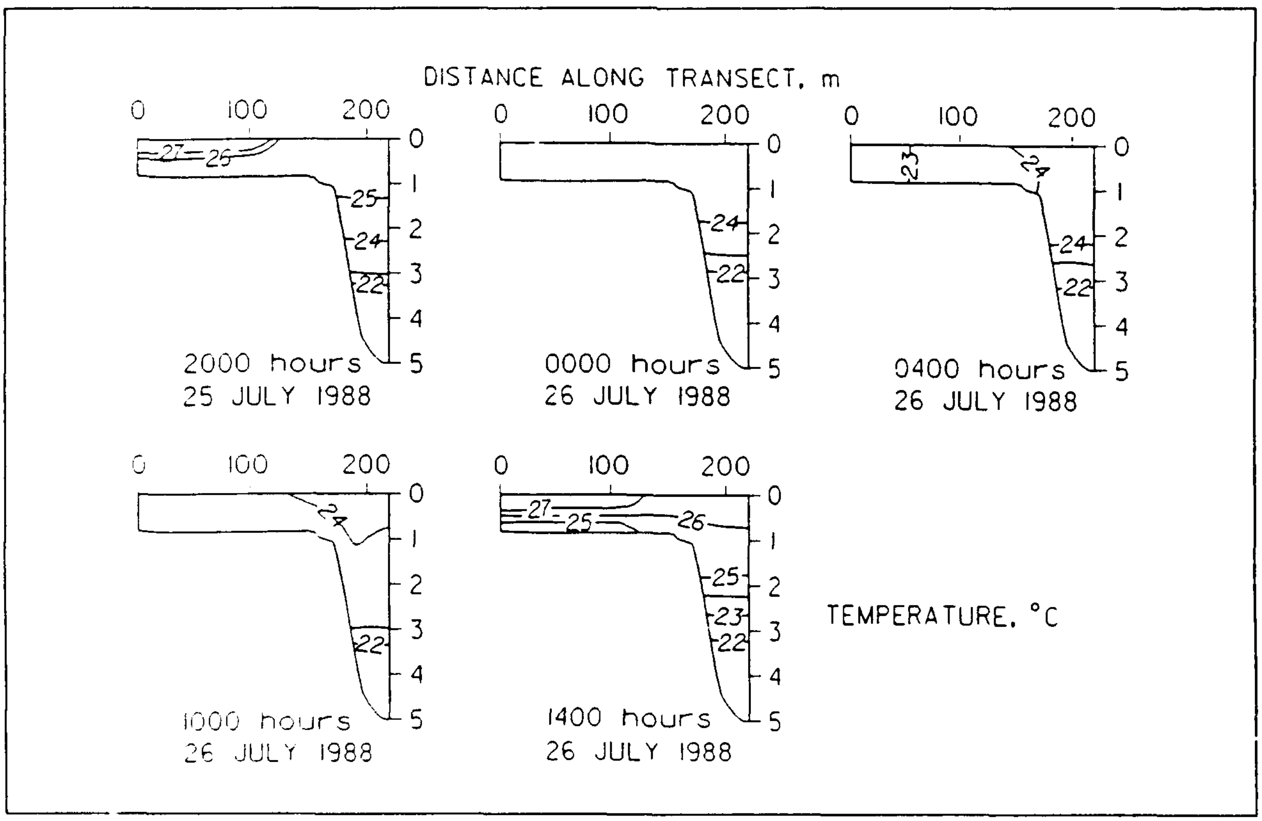


Figure 3. Diel variations in water temperature (°C) versus depth (meters) in the northwest bay during 25-26 July 1988

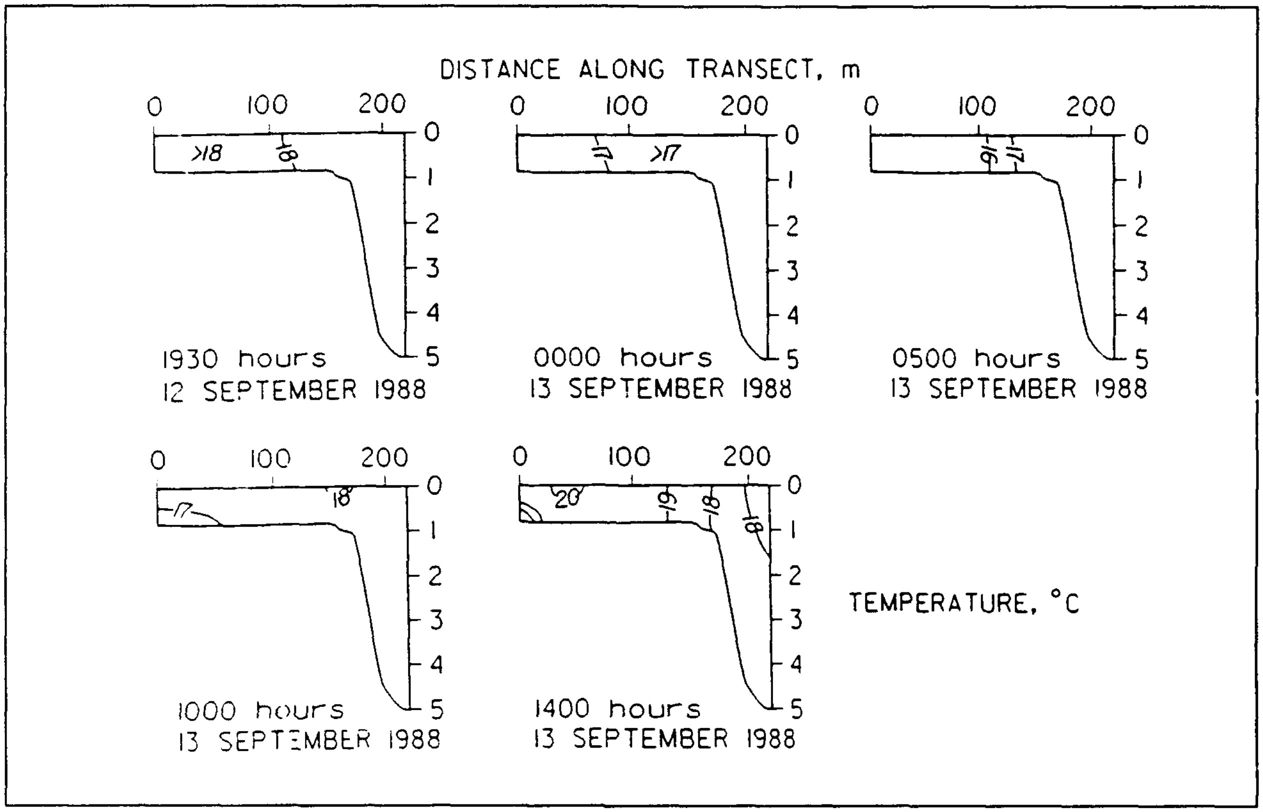
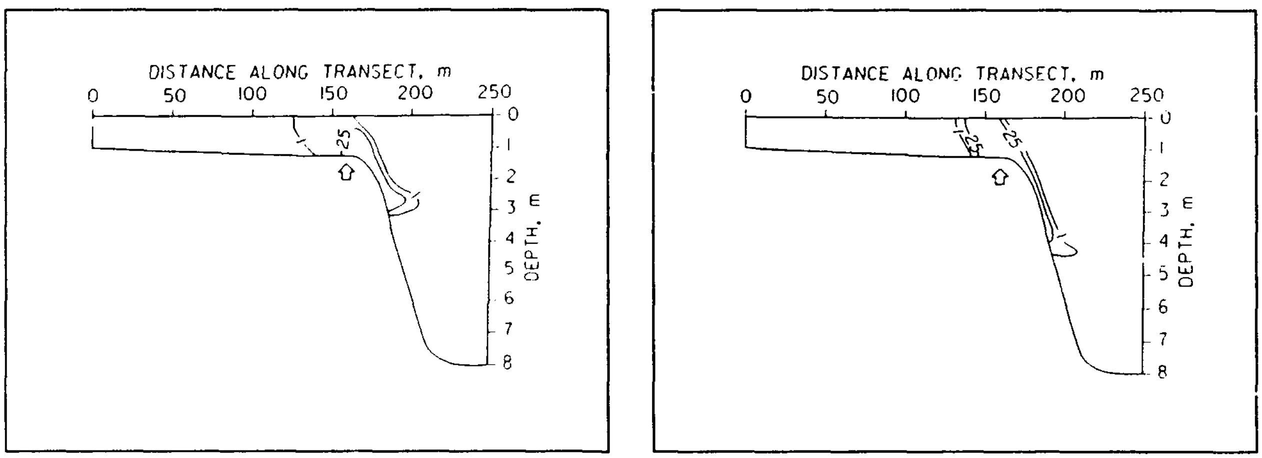


Figure 4. Diel variations in water temperature (°C) versus depth (meters) in the northwest bay during 12-13 September 1988



a. 26 July 1988, 1100 hr

b. 13 September 1988, 1030 hr

Figure 5. Vertical and horizontal variations in dye concentrations (micrograms/liter) in the northwest bay. (Arrow represents dye injection location)

consistently 25 cm in vertical expanse, the cloud moved as an interflow current at different depths in July and September. Due to differences in pelagic thermal stratification between the two study periods (Figures 3 and 4), the interflow occurred at 2.5 m in July and at 4 m in September. During both study periods, reverse dye movement occurred in the upper

75 cm of the water column (Figure 5). Observations of lateral dye concentrations indicated that forward and reverse dye movements were centered on the transect during both sampling periods.

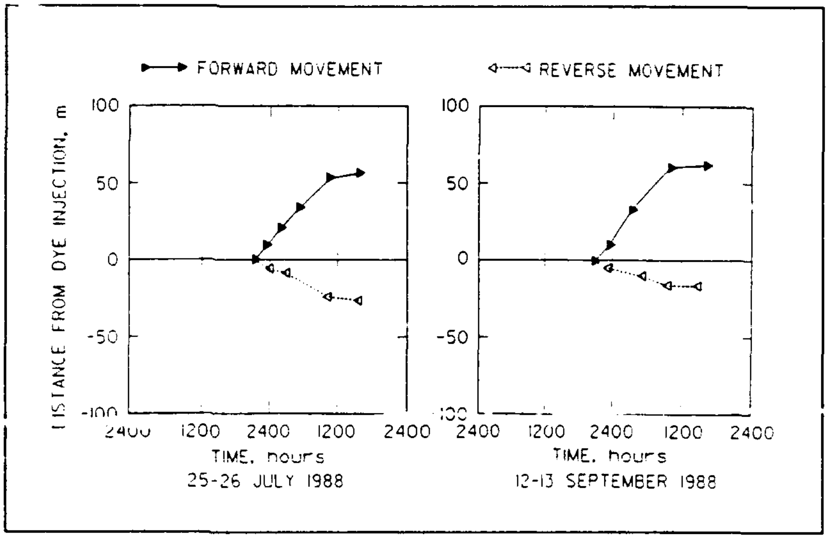


Figure 6. Forward (into the pelagic zone) and reverse (into the littoral zone) movement of dye from injection point versus time during 25-26 July and 12-13 September 1988

Movement of both leading edges occurred linearly with time during both study periods until approximately 1000 hr (Figure 6). Thereafter, dye movement slowed, coincident with littoral zone heating and stratification. Volumetric flow rates were estimated based on the observations during both study periods that the bottom 0.25 m of the littoral water column moved in the forward direction, the top 0.75 m of the pelagic water column moved in the reverse direction, and the length of the littoral-pelagic interface was 1,000 m.

Estimated volumetric flow rates were very similar in both directions during each study period, indicating an approximate balance in the hydrologic budget (Table 1). The combined mean of both forward and reverse volumetric flow rates for both studies was 1,100 $m^3\ hr^{-1}$. Estimated turnover time of the littoral zone, assuming a volume of 97,000 m^3, was 3 to 4 days during both study periods.

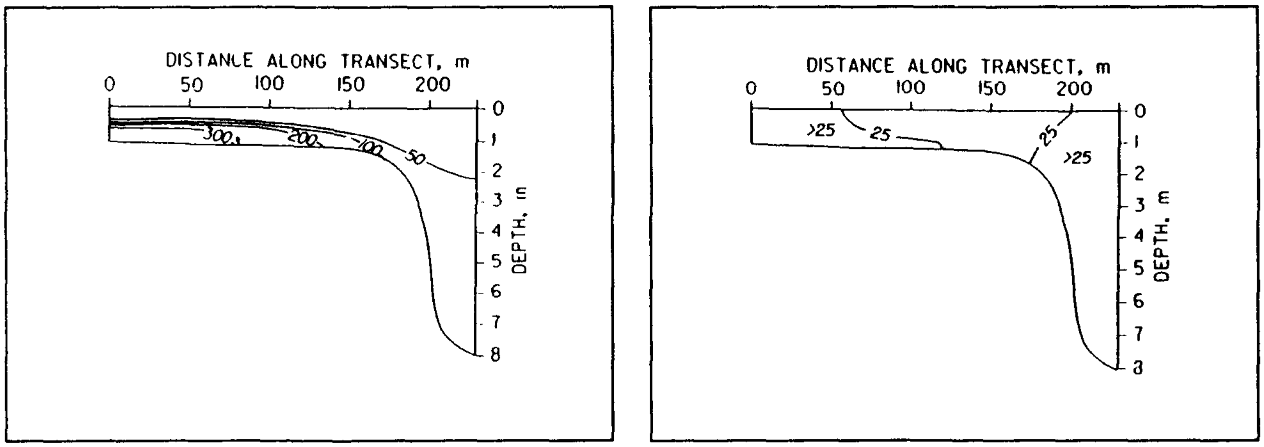
Table 1
Estimation of Volumetric Flow Rates Into the Littoral and Pelagic Zones Based on Observations of Dye Movement on 25-26 July and 12-13 September 1988

Direction of Movement	Flow Velocity $m^3\ sec^{-1}$	Vertical Expanse m	Flow Velocity x Expanse $m^3\ m^{-1}\ sec^{-1}$	Volumetric Flow Rate[1] $m^3\ hr^{-1} \times 10^3$
25-26 July 1988				
Littoral Zone	0.00049	0.75	0.0004	1.3
Pelagic Zone	0.00108	0.25	0.0003	1.0
12-13 September 1988				
Littoral Zone	0.00033	0.75	0.0002	0.9
Pelagic Zone	0.00124	0.25	0.0003	1.1

[1] The volumetric flow rate is the product of flow velocity (adjusted to hours), vertical expanse of measurable dye in the water column, and the length of the littoral-pelagic interface (about 1,000 m) at the outer edge of the macrophyte beds divided by time.

Elevated TP concentrations occurred in the littoral zone above the sediment-water interface during the night of 26 July (Figure 7). Concentrations of TP were lower at similar depths in the pelagic zone on this date, indicating the existence of horizontal as well as vertical gradients. Not only were TP concentrations much lower in September, but vertical and horizontal gradients in TP were less apparent (Figure 7).

Total phosphorus from the bottom 0.25 m of the littoral zone was assumed to move with dye in the forward direction, while TP in the top 0.75 m of the pelagic zone was assumed to move in the reverse direction to estimate TP exchange rates between the littoral and pelagic zones. Overall, hourly rates of both forward and reverse TP exchange were greater in July than in September (Table 2). Forward and reverse TP exchange rates were converted into areal daily TP exchange rates based on the observation that dye



a. 26 July 1988, 0030 hr *b. 13 September 1988, 0030 hr*

Figure 7. Vertical and horizontal variations in TP concentrations (µg L^{-1}) in the northwest bay

movement, and therefore maximal flow velocity, occurred over approximately 12 hr (Figure 5), spanning the nighttime and morning (2200-1000 hr).

Table 2
Estimation of TP Exchange between the Littoral and Pelagic Zones on 25-26 July and 12-13 September 1988, Using Weighted TP Concentrations and Volumetric Flow Rates (see Table 1)

Direction of **Movement**	Weighted TP mg m^{-3}	Volumetric *Flow* $m^3\ hr^{-1} \times 10^3$	*TP Exchange* g hr^{-1}	Areal Daily TP Exchange[1] mg $m^{-2}\ d^{-1}$	Net Areal Daily TP Flux[2] mg $m^{-2}\ d^{-1}$
25-26 July 1988					
Littoral Zone	49	1.3	64	1.3	0
Pelagic Zone	157	1.0	157	3.1	1.8
12-13 September 1988					
Littoral Zone	26	0.9	23	0.5	0
Pelagic Zone	31	1.1	34	0.7	0.2

[1] Areal daily TP exchange is the product of weighted TP concentration, volumetric flow rate, and the period of nighttime convective circulation (12 hr) divided by the reservoir's surface area (0.6 km^2).
[2] Net areal daily TP flux is the difference between littoral and pelagic areal daily TP exchange.

Areal daily TP exchange to the pelagic zone was greater than to the littoral zone during both the July and September study periods (Table 2). Thus, a net areal daily TP flux to the pelagic zone occurred during both studies. The net TP flux to the pelagic zone was much greater in July than in September, due to the existence of higher TP concentrations above the littoral sediment-water interface in July (Table 2).

Discussion

The dynamics of water movement during nighttime cooling periods in July and September provide a mechanism for horizontal P transport to the pelagic zone of Eau Galle Reservoir. The two-layered circulation pattern, described by Horsch and Stefan (1988) and Stefan, Horsch, and Barko (1989), occurred during both study periods. During nighttime cooling, bottom water from the littoral zone moved into the pelagic zone as an interflow, and was replaced by a return flow of pelagic surface water. Since both forward and reverse volumetric flow rates were balanced, convective circulation appeared to be the dominant hydraulic exchange process occurring during these two studies.

Wind speeds decreased to and remained near zero at night for extended periods of time, and therefore were unimportant in inducing hydraulic circulation. In general, the hydraulic flow rates reported here (Table 1) were much lower than those (0.00146 $m^3\ m^{-1}\ sec^{-1}$) estimated for this reservoir from the heat budget model of Stefan, Horsch, and Barko (1989). These differences can perhaps be attributed to seasonal variations in nighttime cooling between the two investigations, or to differences in the flux of heat versus a dye solute.

The entrance of littoral water into the pelagic zone at different intermediate depths (i.e., 2.5 m in July and 4.0 m in September) suggests that weather and stratification patterns were important in the development and placement of interflow currents. During the July study period, the interflow was located at the top of the metalimnion; during the September study period, the lack of a strongly defined metalimnion resulted in a much deeper interflow. Differences in the depth of interflow may be of seasonal importance when considering the availability to the phytoplankton community of entrained nutrients.

The existence of higher TP concentrations in the littoral zone than in the pelagic zone resulted in net areal daily TP fluxes to the pelagic zone. Strong TP gradients occurred above the sediment-water interface in the littoral zone in July, suggesting that sediment provided an important TP source during this study period. Recent evidence indicates that littoral sediment can release substantial P at high pH, even under aerobic conditions (Twinch and Peters 1984, Drake and Heaney 1987).

Although littoral bottom waters of Eau Galle Reservoir were aerobic to within 10 cm of the sediment-water interface, the pH at this depth was 8.5 to 10.0 during both periods. Littoral sediments in this reservoir can release 5 to 8 mg P $m^{-2}\ day^{-1}$ at pH 9 to 10 (James and Barko, unpublished data), suggesting that the sediment probably accounted for much of the P observed in the littoral zone in July.

Estimates of net areal daily TP flux to the pelagic zone via convective circulation are in general agreement with the range of values (0.5 to 5 mg P $m^{-2}\ day^{-1}$) reported for other lakes (Prentki et al. 1979, Stauffer 1987). Wind-driven circulation patterns (Weiler 1978), not considered here, may result in additional littoral P transport. Lakewide internal P loading, calculated by mass balance, averages about 8 mg P $m^{-2}\ day^{-1}$ in Eau Galle Reservoir (James, Barko, and Taylor, in press). Thus, net areal daily TP flux to the pelagic zone potentially accounted for 22 percent (in July) and 2 percent (in September) of the average lakewide internal TP loading.

Our results suggest that circulation patterns induced by nighttime convective cooling are of potentially great importance to the P economy of this reservoir. Although P transport to the pelagic zone occurs primarily at intermediate depths near the base of the epilimnion, this source is available to migrating algal species, which are abundant in Eau Galle Reservoir (Barko et al. 1984; Taylor, Barko, and James 1988; Barko, James, and Taylor 1990). Wind-driven epilimnetic mixing and thermocline migration may also result in vertical entrainment of this P to the epilimnion.

Littoral P fluxes need to be incorporated into models of epilimnetic P transfer, as well as lakewide P mass balance budgets. We are currently investigating P dynamics in the littoral zone and the seasonal importance of convective circulation to gain a better understanding of the importance of this transport mechanism to the P budget of Eau Galle Reservoir.

Acknowledgments

We gratefully acknowledge C. Ellis, G. Horsch, and H. Stefan for valuable discussions; G. Bird, P. Bradley, J. Carroll, H. Eakin, G. Godshalk, R. Green, Y. Hartz, B. Nelson, and R. Olewinski for their participation in the conduct of this study; and G. Nürnberg and H. Stefan for valuable review of this work. Funding was provided by the US Army Engineer Aquatic Plant Control Research Program.

References

American Public Health Association. 1985. *Standard Methods for the Examination of Water and Wastewater*, 16th ed. Washington, DC.

Barko, J. W., and Smart, R. M. 1980. Mobilization of sediment phosphorus by submersed freshwater macrophytes. *Freshwat. Biol.* 10:229-238.

Barko, J. W., Bates, D. J., Filbin, G. J., Hennington, S. M., and McFarland, D. G. 1984. Seasonal growth and community composition of phytoplankton in a eutrophic Wisconsin impoundment. *J. Freshwat. Ecol.* 519-533.

Barko, J. W., James, W. F., and Taylor, W. D. 1990. Effects of alum treatment on phosphorus and phytoplankton dynamics in Eau Galle Reservoir: A synopsis. *Lake Res. Man.* 6:1-8.

Carpenter, S. R. 1980. Enrichment of Lake Wingra, Wisconsin, by submersed macrophyte decay. *Ecology* 61:1145-1155.

Drake, J. C., and Heaney, S. I. 1987. Occurrence of phosphorus and its potential remobilization in the littoral sediments of a productive English lake. *Freshwat. Biol.* 17:513-523.

Effler, S. W., Wodka, M. C., Driscoll, C. T., Brooks, C., Perkins, M., and Owens, E. M. 1986. Entrainment-based flux of phosphorus in Onondaga Lake. *J. Environ. Eng., ASCE* 112:617-622.

Filbin, G. J., and Barko, J. W. 1985. Growth and nutrition of submersed macrophytes in a eutrophic Wisconsin impoundment. *J. Freshwat. Ecol.* 3:275-285.

Horsch, G. M., and Stefan, H. G. 1988. Convective circulation in littoral water due to surface cooling. *Limnol. Oceanogr.* 33:1068-1083.

Imboden, D. M., and Emerson, S. 1978. Natural radon and phosphorus as limnologic tracers: Horizontal and vertical eddy diffusion in Greifensee. *Limnol. Oceanogr.* 23:77-90.

James, W. F., Barko, J. W., and Taylor, W. D. Effects of alum treatment on phosphorus dynamics in a north-temperate reservoir. *Hydrobiologia* (in press).

James, W. F., Kennedy, R. H., and Gaugush, R. F. 1990. Effects of large-scale metalimnetic migrations on phosphorus dynamics in a north-temperate reservoir. *Can. J. Fish. Aquat. Sci.* 47:156-162.

Jassby, A., and Powell, T. 1975. Vertical patterns of eddy diffusion during stratification in Castle Lake, California. *Limnol. Oceanogr.* 20:530-543.

Kennedy, R. H. 1987. Material loadings to Eau Galle Lake. Pages 9-22 *in* R. H. Kennedy and R. C. Gunkel, eds., Limnological *Studies at Eau Galle Lake, Wisconsin;* Report 2, Special Studies and Summary. Technical Report E-85-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kortmann, R. W., Henry, D. D., Kuether, A., and Kaufman, S. 1982. Epilimnetic nutrient loading by metalimnetic erosion and resultant algal responses in Lake Waramaug, Connecticut. *Hydrobiol.* 92:501-510.

Landers, D. H. 1982. Effects of naturally senescing aquatic macrophytes on nutrient chemistry and chlorophyll *a* of surrounding waters. *Limnol. Oceanogr.* 27:428-439.

Mortimer, C. H. 1971. Chemical exchanges between sediments and water in the Great Lakes - Speculations on probable regulatory mechanisms. *Limnol. Oceanogr.* 16:387-405.

Nürnberg, G. K. 1984. The prediction of internal phosphorus loading in lakes with anoxic hypolimnia. *Limnol. Oceanogr.* 29:111-124.

Nürnberg, G. K. 1987. A comparison of internal phosphorus loads in lakes with anoxic hypolimnia: Laboratory incubation versus in situ hypolimnetic phosphorus accumulation. *Limnol. Oceanogr.* 32:1160-1164.

Nürnberg, G. K., Shaw, M., Dillon, P. J., and McQueen, D. J. 1986. Internal phosphorus load in an oligotrophic Precambrian Shield lake with an anoxic hypolimnion. *Can. J. Fish. Aquat. Sci.* 43:574-580.

Patterson, K. J., and Brown, J. M. A. 1979. Growth and elemental composition of *Lagarosiphon major,* in response to water and substrate nutrients. *Prog. Wat. Tech.* 2:231-246.

Prentki, R. T., Adams, M. S., Carpenter, S. R., Gasith, A., Smith, C. S., and Weiler, P. R. 1979. The role of submersed weedbeds in internal loading and interception of allochthonous materials in Lake Wingra, Wisconsin, USA. *Arch. Hydrobiol. (Suppl.)* 57:221-250.

Riley, E. T., and Prepas, E. E. 1984. Role of internal phosphorus loading in two shallow, productive lakes in Alberta, Canada. *Can. J. Fish. Aquat. Sci.* 41:845-855.

Robards, R. D., and Ward P. R. B. 1978. Vertical diffusion and nutrient transport in a tropical lake (Lake McIlwaine, Rhodesia). *Hydrobiologia* 59:213-221.

Smith, C. S., and Adams, M. S. 1986. Phosphorus transfer from sediments by *Myriophyllum spicatum. Limnol. Oceanogr.* 31:1312-1321.

Stauffer, R. E. 1985. Nutrient internal cycling and the trophic regulation of Green Lake, Wisconsin. *Limnol. Oceanogr.* 30:347-363.

Stauffer, R. E. 1987. Vertical nutrient transport and its effect on epilimnetic phosphorus in four calcareous lakes. *Hydrobiologia* 154:87-102.

Stauffer, R. E., and Armstrong, D. C. 1984. Lake mixing and its relationship to epilimnetic phosphorus in Shagawa Lake, Minnesota. *Can. J. Fish. Aquat. Sci.* 41:57-69.

Stauffer, R. E., and Lee, G. R. 1973. Role of thermocline migration in regulating algal blooms. Pages 73-82 *in* E. J. Middlebrooks, D. H. Falkenburg, and T. E. Maloney, eds., *Modeling the Eutrophication Process*. Ann Arbor Science Publishers, Ann Arbor, Michigan.

Stefan, H. G., and Hanson, M. J. 1981. Phosphorus recycling in five shallow lakes. *J. Environ. Eng., ASCE* 107:713-731.

Stefan, H.G., Horsch, G. M., and Barko, J. W. 1989. A model for the estimation of convective exchange in the littoral region of a shallow lake during cooling. *Hydrobiologia* 174:225-234.

Taylor, W. D., Barko, J. W., and James, W. F. 1988. Contrasting diel patterns of vertical migration in the dinoflagellate *Ceratium hirundinella* in relation to phosphorus supplies in a north temperate reservoir. *Can. J. Fish. Aquat. Sci.* 45:1093-1098.

Theis, T. L., and McCabe, P. J. 1978. Phosphorus dynamics in hypereutrophic lake sediments. *Wat. Res.* 12:667-685.

Twinch, A. J., and Peters, R. H. 1984. Phosphate exchange between littoral sediments and overlying water in an oligotrophic north-temperate lake. *Can. J. Fish. Aquat. Sci.* 41:1609-1617.

Weiler, P. R. 1978. Littoral-pelagic exchange in Lake Wingra, Wisconsin, as determined by a circulation model. Report 100. Inst. Environ. Studies, Univ. Wisconsin, Madison.

Wetzel, R. G. 1979. The role of the littoral zone and detritus in lake metabolism. *Arch. Hyrobiol.* 13:145-161.

Wodka, M. C., Effler, S. W., Driscoll, C., Field, S. D., and Devan, S. P. 1983. Diffusivity-based flux of phosphorus in Onondaga Lake. *J. Environ. Eng., ASCE* 109:1403-1415.

Sediment Interactions with Submersed Macrophytes

by
John W. Barko[1]

Introduction

Submersed macrophytes are unique among rooted aquatic vegetation because they link the sediment with overlying water. This linkage is responsible for great complexities in nutrition, and has potentially important implications for nutrient cycling. During the past two decades, it has become clear that, in addition to serving as a base for physical attachment, sediment also provides a source of nutrient supply to submersed macrophytes (see Barko 1991). It is now recognized that sediment fertility exerts an important influence on macrophyte productivity and species composition. However, the mechanisms involved (see below) are complex.

In this paper, effects of sediment fertility on submersed macrophyte productivity are addressed, with specific attention to nitrogen (N) and phosphorus (P) as potentially limiting elements. In addition, evidence is provided for autogenic reductions in sediment nutrient availability; consequences to macrophyte production rate are considered; and processes potentially involved in balancing sediment nutrient deficiencies are reviewed. These topics are considered with a view toward the development of novel macrophyte management approaches.

Effects of Sediment Fertility

In laboratory investigations, Barko and Smart (1986) demonstrated relatively poor growth of *Hydrilla verticillata* and *Myriophyllum spicatum* on highly organic sediments and on sands compared with growth on fine-textured inorganic sediments. The growth of these species decreased almost linearly with increasing sediment organic matter up to a concentration of about 20 percent. From fertilization experiments, they concluded that macrophyte growth limitation on sands and organic sediments resulted from nutrient deficiencies.

Since organic matter and sand (i.e., coarse-textured sediment) have opposing influences on sediment density, their effects on macrophyte growth can be generalized as a function of sediment density (Figure 1).

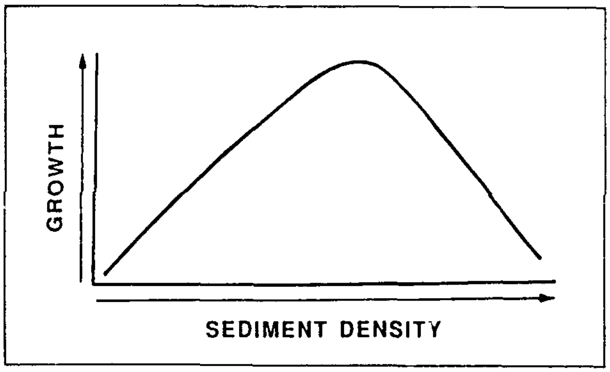


Figure 1. Idealized relationship between submersed macrophyte growth and sediment density (after Barko and Smart 1986). Density increase up to about 0.9 g/ml reflects decreasing sediment organic matter content. Density increase beyond this value reflects increasing sediment texture. Macrophyte growth is maximal on fine-textured sediments with density ranging between approximately 0.8 and 1.0 g/ml

Sands possess high bulk density and low nutrient availability. However, the actual fertility of sands may vary considerably in nature with groundwater nutrient inputs to the root zone (e.g., Lodge et al. 1988; Lillie and Barko, in press). Organic sediments possess

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

low bulk density, and their nutrient content (commonly considered to be high) is actually quite low on the basis of sediment volume (DeLaune, Buresh, and Patrick 1979; Barko and Smart 1986). Nutrient uptake by rooted submersed macrophytes growing on low-density organic sediments is potentially hindered by the long distances over which nutrients must diffuse (cf. Barko and Smart 1986).

Owing to the large exchangeable pool of phosphorus in most lake sediments (e.g., Carignan and Flett 1981), it is unlikely that submersed macrophytes are often limited in their growth by P availability. Indeed, attempts to stimulate submersed macrophyte growth in situ by P addition to sediment (e.g., Anderson and Kalff 1986; Moeller, Burkholder, and Wetzel 1988), or to retard growth by reducing sediment P availability (Mesner and Narf 1987), have been generally unsuccessful. In contrast, fertilization of sediment by addition of N alone or in combination with other elements has been shown to significantly increase the growth of submersed macrophytes (Anderson and Kalff 1986; Duarte and Kalff 1988; Moeller, Burkholder, and Wetzel 1988). These results, in combination with results of laboratory studies (Barko, unpublished data), suggest that the availability of nitrogen in sediments may under many circumstances limit the growth of submersed macrophytes.

Autogenic Reductions in Sediment Nutrient Availability

Given the significance of sediment in supplying N, P, and possibly other nutrients to submersed macrophytes, it is important to evaluate the effects of macrophyte growth on sediment nutrient availability. The capacity of some submersed macrophyte species to form chemical precipitates through direct oxidation of sediment has been demonstrated by Tessenow and Baynes (1975, 1978). By elevating sediment redox potential, submersed macrophytes under some conditions are capable of reducing concentrations of soluble P in the sediment interstitial water (Jaynes and Carpenter 1986). The clearest evidence and most dramatic examples of sediment oxidation (redox increase) by submersed macrophytes derive from studies conducted in oligotrophic lakes (e.g., Wium-Anderson and Andersen 1972, Jaynes and Carpenter 1986). In contrast, the redox status of fertile sediments from eutrophic lakes may not respond to oxygen released by submersed macrophytes (Carpenter 1983, Chen and Barko 1988).

Evidence from field studies is accumulating to suggest that rooted submersed macrophytes, even with relatively diminutive root systems, are capable of markedly depleting pools of N and P in sediments (Prentki 1979, Trisal and Kaul 1983, Carignan 1985). By way of confirmation, recent laboratory studies have demonstrated greater than 90 and 30 percent reductions in concentrations of exchangeable N and extractable P, respectively, from sediment over two 6-week periods of growth of *Hydrilla verticillata* (Barko et al. 1988). Since this species is essentially unable to elevate sediment redox potential (Chen and Barko 1988), nutrient uptake alone appears to account for its effect on sediment nutrient status.

Even in fertile systems where effects of submersed macrophytes on sediment redox status are probably minimal, depletion of sediment nutrient pools resulting from aquatic macrophyte uptake may significantly reduce sediment nutrient availability. High productivity and biomass turnover of aquatic macrophytes in fertile systems further contribute to high rates of nutrient loss from sediments (Smith and Adams 1986). In general, it appears that N is depleted from sediments to a much greater extent than P (relative to macrophyte nutritional needs). Thus, N is more likely than P to limit macrophyte growth (also see above).

Processes Potentially Balancing Sediment Nutrient Deficiencies

Effects of sedimentation

Sedimentation provides an important means of nutrient renewal to the littoral zone, and in large part may balance nutrient losses due to macrophyte uptake. Factors affecting sedimentation have been studied extensively in the open water (e.g., Hakanson 1977; Kamp-Nielson and Hargrave 1978), but to a much lesser extent in the littoral zone of lakes. Aquatic macrophyte beds serve as effective traps for inflowing dissolved and particulate materials (Patterson and Brown 1979; Wetzel 1979; Carpenter 1981). Moeller and Wetzel (1988) recently suggested that sedimentation of algae from macrophyte leaf surfaces may provide an important link for transfer of nutrients absorbed from the water (by algae) to the sediment surface. Similarly, it has been reported that under conditions of nutrient enrichment, decomposing filamentous algae can provide major inputs of N and P to sediment (Howard-Williams 1981).

By reducing turbulence, aquatic macrophytes also serve an important role in sediment stabilization (Madson and Warncke 1983). Sedimentation rates in the littoral zone have been shown to be about twofold greater than rates of sedimentation in the adjacent erosional zone of a reservoir (James and Barko 1990). In contrast with the opinion that physical disturbance in erosional zones directly limits submersed macrophyte development (e.g., Spence 1982), Duarte and Kalff (1988) have recently suggested that erosion of fine-textured particles and associated nutrients may limit macrophyte growth by promoting nutritional deficiencies. Greater sedimentation with less erosion in gently sloped, rather than sharply sloped, littoral regions may account for the relationship established between littoral slope and the biomass of submersed macrophyte communities (Duarte and Kalff 1986).

Effects of benthic invertebrate activities

Activities of benthic invertebrates can significantly influence physical and chemical properties of sediment, thereby potentially affecting the availability of nutrients to aquatic macrophytes. For example, the case construction and tube irrigation activities of chironomids can accelerate nutrient transport within sediment by increasing the area of the sediment-water interface, horizontal and vertical diffusional fluxes of nutrients within sediment, and sediment porosity (Fukuhara and Sakamoto 1987). In addition, the vertical mixing of sediment by tubificid worms (McCall and Fisher 1980) continuously increases levels of nutrients in the sediment interstitial water (Fukuhara and Sakamoto 1987).

As depicted in Figure 2, the activity of tubificid worms in concert with microbial and chemical processes causes the release of soluble nutrients from particulate phases in the sediment. Dissolved nutrients may then diffuse to the sediment surface or, in the presence of rooted macrophytes, be taken up by roots. In addition, these worms effect a directional reworking of sediment particles that produces deposition of material at the sediment surface and an orderly vertical mixing of the upper 5 to 10 cm of sediment. These physical effects by both groups of invertebrates can result in vertical transport of recently deposited materials to depth in the sediment (Krantzberg 1985). Sediment reworking by benthic invertebrates in the littoral zone may be important in intermixing newly accreted sediment in the root zone of aquatic macrophytes.

Benthic invertebrates can also increase the redox potential of surface sediment by circulating oxygen-rich water into the sediment (Hargrave 1972, Davis 1974, Fukuhara and Sakamoto 1987). Redox potential is a major factor controlling availability of many nutrients in sediments; thus, the extension of oxidizing conditions to deeper levels in sediment may serve to decrease nutrient availability (cf. Jaynes and Carpenter 1986).

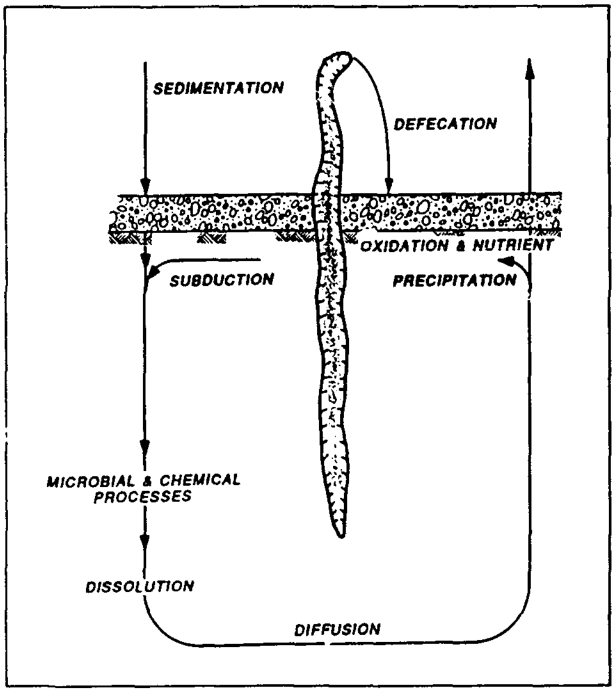


Figure 2. Conceptual model of the effect of tubificid sediment mixing on inorganic substances released to solution by chemical and microbial processes (after McCall and Fisher 1980). Other benthic invertebrates influence profiles of inorganic constituents in sediment interstitial waters through different mechanisms (see text)

Since ammonium-oxidizing bacteria require the simultaneous presence of both ammonium and dissolved oxygen, the potential exists for populations of these bacteria to develop along burrow walls and in upper pelletized layers, resulting in increased rates of ammonium oxidation to nitrite and nitrate. The latter forms of N are less favored than ammonium for uptake b aquatic macrophytes (Nichols and Keeney 1976). In addition, nitrate can diffuse back into nearby anaerobic zones where denitrifying bacteria may reduce nitrate to nitrogen gas, resulting in loss of nitrogen from the sediment (Reddy and Patrick 1984). The net effect of these processes on nutrient availability to aquatic macrophytes has not been evaluated.

Effects of microbial activities

Through their role in decomposition and nutrient cycling, microorganisms make available in sediments a variety of elements important to the nutrition of submersed aquatic macrophytes (Gunnison and Barko 1989). Among these, N and P are highly significant as major growth-limiting factors in the aquatic environment. Chemical reduction of sediment through microbial metabolism is an important condition for plant growth, permitting accumulation of these key nutrients to levels that maximize the growth potential of submersed macrophytes.

Many nutrient transformations, fueled by decompositional processes, are carried out by microorganisms that reach high population levels only in the root zone. Durako and Moffler (1987) have suggested that microflora-plant root relationships may be obligatory to the nutrition (particularly N) of aquatic macrophytes. Others have suggested that increased bacterial abundance in areas of increased macrophyte biomass may increase the volume of nutrient recycling (Carigan 1985; Duarte, Bird, and Kalff 1988).

Nitrogen fixation occurs within the root zone of a variety of submersed macrophytes (Smith and Hayasaka 1982a,b; Schmidt and Hayasaka 1985). Other studies have indicated that deamination of amino acids carried out by microflora may provide a major source of ammonium for these plants (Smith, Hayasaka, and Thayer 1984; Boon, Moriarity, and Saffigna 1986). In the root zone of the submersed freshwater macrophyte *Myriophyllum alterniflorum*, Blotnick, Rho, and Gunner (1980) identified the occurrence of a variety of microbial processes of significance to macrophyte nutrition. These processes included ammonification, denitrification, nitrogen fixation, and acid production (important in the liberation of metals and phosphate from minerals).

Management Perspectives

To date, studies of submersed macrophyte nutrition have focused almost entirely on sources of nutrient acquisition. The nutrients of greatest importance in the nutritional ecology of these plants are N and P, which are largely sediment-derived. A complex variety

of processes (reviewed above) regulate sediment nutrient dynamics, and these processes bear directly on submersed macrophyte productivity. Sedimentation, benthic invertebrate activities, and microbial activities in sediment have been studied extensively, but only to a limited extent with respect to influences on aquatic macrophyte nutrition. These processes appear to act in concert in regulating nutrient supplies to rooted macrophytes in littoral sediments. The sustained vigor of submersed macrophyte communities depends on, among other factors, the balance between nutrient losses and gains. Changes in this balance affected by watershed influences or human interventions need to be considered within the context of macrophyte management.

Over geological time, the vector of vegetative change toward basin filling in lacustrine ecosystems is clear. However, many important scientific and management questions are more relevant to shorter time scales. Invasions of nuisance macrophytes, for example, often have cycles of a decade or so. Compositional changes in aquatic macrophyte communities over short time intervals remain largely unexplained. Macrophyte-sediment interactions at both population and community levels appear to be powerful and complex. Thus, a better understanding of these interactions should be useful in explaining short-term compositional changes, including species invasions and declines.

Acknowledgments

This paper derives in part from a review submitted to the journal *Aquatic Botany*. Douglas Gunnison of WES and Stephen Carpenter of the University of Wisconsin-Madison, coauthors of the review article, contributed to the development of portions of the present text.

References

Anderson, M. R., and Kalff, J. 1986. Nutrient limitation of *Myriophyllum spicatum* growth in situ. *Freshwater Biol.* 16:735-743.

Barko, J. W. 1991. See pp 87-94 in this proceedings.

Barko, J. W., and Smart, R. M. 1986. Sediment-related mechanisms of growth limitation in submersed macrophytes. *Ecology* 67:1328-1340.

Barko, J. W., Smart, R. M., McFarland, D. G., and Chen, R. L. 1988. Interrelationships between the growth of *Hydrilla verticillata* (L.f.) Royle and sediment nutrient availability. Aquat. Bot. 32:205-216.

Blotnick, J. R., Rho, J., and Gunner, H. B. 1980. Ecological characteristics of the rhizosphere microflora of *Myriophyllum heterophyllum*. *J. Environ. Qual.* 9:207-210.

Boon, P. I., Moriarity, D. J. W., and Saffigna, P. G. 1986. Rates of ammonium turnover and the role of amino-acid deamination in seagrass (*Zostera capricorni*) beds of Moreton Bay, Australia. *Mar. Biol.* 91:259-268.

Carignan, R. 1985. Nutrient dynamics in a littoral sediment colonized by the submersed macrophyte *Myriophyllum spicatum*. *Can. J. Fish. Aquat. Sci.* 42:1303-1311.

Carignan, R., and Flett, R. F. 1981. Postdepositional mobility of phosphorus in lake sediments. *Limnol. Oceanogr.* 29:667-670.

Carpenter, S. R. 1981. Submersed vegetation: An internal factor in lake ecosystem succession. *Am. Nat.* 118:372-383.

Carpenter, S. R. 1983. Submersed macrophyte community structure and internal loading: Relationship to lake ecosystem productivity and succession. In: J. Taggart (ed.), Lake Restoration, Protection, and Management. US Environmental Protection Agency, Washington, DC, pp 105-111.

Chen, R. L., and Barko, J. W. 1988. Effects of freshwater macrophytes on sediment chemistry. *J. Freshwater Ecol.* 4:279-289.

Davis, R. B. 1974. Tubificids alter profiles of redox potential and pH in profundal lake sediment. *Limnol. Oceanogr.* 19:342-346.

DeLaune, R. D., Buresh, R. J., and Patrick, Jr., W. H. 1979. Relationship of soil properties to standing crop biomass of *Spartina alterniflora* in a Louisiana marsh. *Estuar. Coast. Mar. Sci.* 8:488-482.

Duarte, C. M., and Kalff, J. 1986. Littoral slope as a predictor of the maximum biomass of submerged macrophyte communities. *Limnol. Oceanogr.* 31:1072-1080.

Duarte, C. M., and Kalff, J. 1988. Influence of lake morphometry on the response of submerged macrophytes to sediment fertilization. *Can. J. Fish. Aquat. Sci.* 45:216-221.

Duarte, C. M., Bird, D. F., and Kalff, J. 1988. Submerged macrophytes and sediment bacteria in the littoral zone of Lake Memphremagog (Canada). *Verh. Internat. Verein. Limnol.* 23:271-281.

Durako, M. J., and Moffler, M. D. 1987. Nutritional studies of the submerged marine angiosperm *Thalassia testudinum;* I. Growth responses of axenic seedlings to nitrogen enrichment. *Amer. J. Bot.* 74:234-240.

Fukuhara, H., and Sakamoto, M. 1987. Enhancement of inorganic nitrogen and phosphate release from lake sediment by tubificid worms and chironomid larvae. *Oikos* 48:312-320.

Gunnison, D., and Barko, J. W. 1989. The rhizosphere ecology of submersed macrophytes. *Water Resources Bull.* 25:193-201.

Hakanson, L. 1977. The influence of wind, fetch, and water depth on the distribution of sediment in Lake Vanern, Sweden. *Can. J. Earth Sci.* 14:397-412.

Hargrave, B. T. 1972. Oxidation-reduction potentials, oxygen concentration, and oxygen uptake of profundal sediments in a eutrophic lake. *Oikos* 23:167-177.

Howard-Williams, C. 1981. Studies on the ability of a *Potamogeton pectinatus* community to remove dissolved nitrogen and phosphorus compounds from lake water. *J. Appl. Ecol.* 18:619-637.

James, W. F., and Barko, J. W. 1990. Macrophyte influences on the zonation of sediment accretion and composition in a north-temperate reservoir. *Archiv. Hydrobiol* (in press).

Jaynes, M. L., and Carpenter, S. R. 1986. Effects of vascular and nonvascular macrophytes on sediment redox and solute dynamics. *Ecology* 67:875-882.

Kamp-Nielson, L., and Hargrave, B. T. 1978. Influence of bathymetry on sediment focusing in Lake Esrom. *Verh. Internat. Verein. Limnol.* 20:714-719.

Krantzberg, G. 1985. The influence of bioturbation on physical, chemical, and biological parameters in aquatic environments: A review. *Environ. Pollut. (Ser. A)* 39:99-122.

Lillie, R. A., and Barko, J. W. Influence of sediment and groundwater on the distribution and biomass of *M. spicatum* L. in Devils Lake, Wisconsin. *J. Freshwater Ecol.* (in press).

Lodge, D. M., Barko, J. W., Strayer, D., Melack, J. M., Mittelbach, G. G., Howarth, R. W., Menge, B., and Titus, J. E. 1988. Spatial heterogeneity and habitat interactions in lake communities. Pages 181-208 in S. R. Carpenter (ed.), *Complex Interactions in Lake Communities.* Springer-Verlag, New York.

Madson, T. V., and Warncke, E. 1983. Velocities of currents around and within submerged aquatic vegetation. *Arch. Hydrobiol.* 97:389-394.

McCall, P. L., and Fisher, J. B. 1980. Effects of tubificid oligochaetes on physical and chemical properties of Lake Erie sediments. Pages 253-317 in R. O. Brinkhurst and D. G. Cooke (eds.), *Aquatic Oligochaete Biology.* Plenum Press, New York.

Mesner, N., and Narf, R. 1987. Alum injection into sediments for phosphorus inactivation and macrophyte control. *Lake and Reservoir Manage.* 3:256-265.

Moeller, R. E., and Wetzel, R. G. 1988. Littoral vs. profundal components of sediment accumulation: Contrasting roles as phosphorus sinks. *Verh. Internat. Verein. Limnol.* 23:386-393.

Moeller, R. E., Burkholder, J. M., and Wetzel, R. G. 1988. Significance of sedimentary phosphorus to a rooted submersed macrophyte (*Najas flexilis* (Willd.) Rostk. and Schmidt) and its algal epiphytes. *Aquat. Bot.* 32:261-281.

Nichols, D. S., and Keeney, D. R. 1976. Nitrogen nutrition of *Myriophyllum spicatum:* Variation of plant tissue nitrogen concentration with season and site in Lake Wingra. *Freshwater Biol.* 6:137-144.

Patterson, K. J., and Brown, J. M. A. 1979. Growth and elemental composition of *Lagarosiphon major,* in response to water and substrate nutrients. *Prog. Water Technol.* 2:231-246.

Prentki, R. T. 1979. Depletion of phosphorus from sediment colonized by *Myriophyllum spicatum* L. Pages 161-176 in J. E. Breck, R. T. Prentki, and O. L. Loucks (eds.), *Aquatic Plants, Lake Management, and Ecosystem Consequences of Lake Harvesting.* Institute for Environmental Studies, University of Wisconsin, Madison, WI.

Reddy, K. R., and Patrick, W. H., Jr. 1984. Nitrogen transformation and losses in flooded soils and sediments. *CRC Crit. Rev. Envir. Contr.* 13:273-309.

Schmidt, M. A., and Hayasaka, S. S. 1985. Localization of a dinitrogen-fixing *Klebsiella* sp. isolated from root-rhizomes of the seagrass *Halodule wrightii* Aschers. *Bot. Mar.* 28:437-442.

Smith, C. S., and Adams, M. S. 1986. Phosphorus transfer from sediments by *Myriophyllum spicatum. Limnol. Oceanogr.* 31:1312-1321.

Smith, G. W., and Hayasaka, S. S. 1982a. Nitrogenase activity associated with *Halodule wrightii* roots. *Appl. Environ. Microbiol.* 43:1244-1248.

Smith, G. W., and Hayasaka, S. S. 1982b. Nitrogenase activity associated with *Zostera marina* from a North Carolina estuary. *Can. J. Microbiol.* 28:448-451.

Smith, G. W., Hayasaka, S. S., and Thayer, G. W. 1984. Ammonification of amino acids by the rhizoplane microflora of *Zostera marina* L. and *Halodule wrightii* Aschers. *Bot. Mar.* 27:23-27.

Spence, D. H. N. 1982. The zonation of plants in freshwater lakes. *Adv. Ecol. Res.* 12:37-125.

Tessenow, V., and Baynes, Y. 1975. Redox-dependent accumulation of Fe and Mn in a littoral sediment supporting *Isoetes lacustris* L. *Naturwiss.* 62:342-343.

Tessenow, V., and Baynes, Y. 1978. Experimental effects of *Isoetes lacustris* L. on the distribution of Eh, pH, Fe, and Mn in lake sediment. *Verh. Internat. Verein. Limnol.* 20:2358-2362.

Trisal, C. L., and Kaul, S. 1983. Sediment composition, mud-water interchanges and the role of macrophytes in Dal Lake, Kashmir. *Int. Revue Ges. Hydrobiol.* 68:671-682.

Wetzel, R. G. 1979. The role of the littoral zone and detritus in lake metabolism. *Arch. Hydrobiol.* 13:145-161.

Wium-Anderson, S., and Andersen, J. M. 1972. The influence of vegetation on the redox profile of the sediment of Grane Langso, a Danish Lobelia lake. *Limnol. Oceanogr.* 17:948-952.

Ecological Perspectives in Aquatic Plant Management

by
Craig S. Smith[1]

Introduction

Efficient management of nuisance aquatic plants requires an understanding of their ecology. Management-oriented ecological studies of nuisance plants must identify natural population controls in order to devise ways to optimize management strategies.

Contrary to the widely held perception that nuisance aquatic plants grow essentially without limitation, there is considerable evidence of the existence of natural population controls for these species. Previous research has demonstrated the potential of many environmental factors to limit nuisance plant growth; future research must focus increasingly on identifying the role of these and other factors in limiting nuisance plant growth in the field. Once key natural population controls have been identified, management strategies can be designed to act in concert with these controls.

Identification of Natural Population Controls

Clues to the identity of natural population controls can be gained by studying naturally occurring variations in plant vigor. Some general factors influencing the success of Eurasian watermilfoil (*Myriophyllum spicatum L.*) invasions can be inferred from existing evidence (Table 1). In general, little is known about the specific mechanisms governing the effects of these factors.

Table 1
Factors Influencing the Success of Eurasian Watermilfoil Invasions

Factor	Influence on Eurasian Watermilfoil Success
Fertility	Nuisance growths of the plant are primarily restricted to fertile lakes, or fertile locations in less fertile lakes.
Disturbance	Invasion is facilitated when disturbances open up habitat.
Human activities	Human activities spread the species between lakes.

Fertility

Smith and Barko (1990) asserted that *M. spicatum* attains maximum abundance in lakes of moderately high fertility (Figure 1). In less fertile lakes, *M. spicatum* growth is presumably limited by the availability of nutrients, particularly in sediments, while low light availability (due to low water clarity and abundant epiphytic growth) limits plant success in very productive lakes. The response to fertility is not a change in the maximum density or biomass of milfoil in dense beds, but rather a change in the frequency of conditions capable of supporting luxuriant milfoil

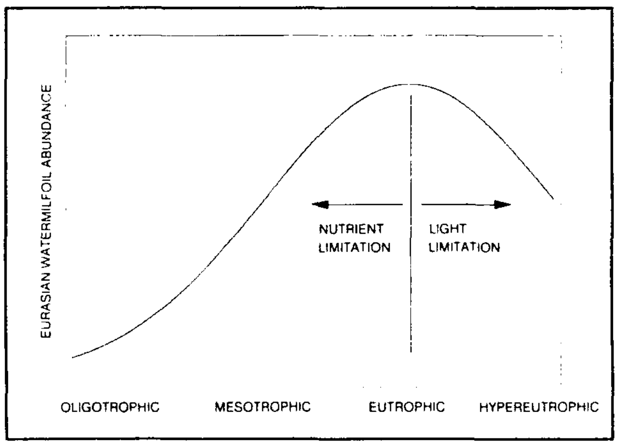


Figure 1. Theoretical relationship between Eurasian watermilfoil abundance and fertility

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

growth. In oligotrophic Lake George, New York, *M. spicatum* attains very high levels of biomass where it grows in dense beds, but dense beds cover only a very small fraction of the littoral zone (Madsen et al. 1989). In contrast, dense beds of *M. spicatum* covered virtually the entire submersed plant zone of eutrophic Lake Wingra, Wisconsin (Gustafson and Adams 1973), prior to its decline there.

Disturbance

There is widespread agreement that aggressive exotic plant species such as *M. spicatum* and *Hydrilla verticillata* readily invade open habitat. It is not equally clear that they routinely invade intact, undisturbed communities of native aquatic plants. Perhaps the best documented cases where *M. spicatum* nearly completely replaced native species occurred in Lakes Mendota and Wingra (see Lind and Cottam 1969, Nichols and Mori 1971), two highly disturbed water bodies. Disturbances to Lake Wingra included water-level alteration, carp introduction, large-scale carp removal and extensive land-use changes in the drainage basin (Baumann et al. 1974). In some other lakes, native aquatic plants were not replaced when *M. spicatum* invaded (Table 2). It is not definitely known whether disturbance is the key factor determining whether replacement occurs, but it is certainly a major factor.

Table 2
Replacement of Native Plant Species by Eurasian Watermilfoil

Location	Replacement	Remarks
Lakes Wingra[1] and Mendota,[2] Wisconsin	Yes	Near complete replacement of *Potamogeton*, *Vallisneria*
Devil's Lake[3], Wisconsin	Slight	Displaced some *Elodea*
TVA Reservoirs[4]	No	Invaded new habitat as reservoirs flooded
Lakes Opinicon, Ontario[5]	No	Invaded open habitat in deep water

[1] Nichols and Mori 1971.
[2] Lind and Cottam 1969.
[3] Lillie 1986.
[4] A. L. Bates, personal communication.
[5] Keast 1984.

Disturbances typically favor invasive species, which spread and grow rapidly (Grime 1979). In water bodies with well-established native plant populations, managers should be very hesitant to use control techniques that disturb the native plant species, as such disturbances are likely to hasten the spread of aggressive nuisance plant species.

Fragment transport

Human-mediated transport of plant fragments is among the main means of dispersal for *M. spicatum* (Johnstone et al. 1985), as it probably is for other submersed nuisance species. Although the steps necessary to minimize transport of fragments are relatively obvious, efforts to block this dispersal pathway have met with only limited success (Newroth 1985). Even if the transport of fragments by humans was completely eliminated, other dispersal mechanisms (e.g., transport of fragments and seeds by waterfowl) would likely spread the species to new locations, albeit more slowly.

Natural Declines

The study of spontaneously occurring submersed plant declines is a particularly promising avenue for the discovery of natural population controls. *Myriophyllum spicatum* populations characteristically decline approximately 10 to 15 years after dominance (Carpenter 1980). The reasons for the decline are essentially unknown, although a number of possible causes have been suggested (Table 3). Several of these seem more likely than others.

Nutrient depletion from sediments may be an important factor contributing to declines by several possible mechanisms. Previous studies have focused on phosphorus (P) nutrition, and found that P concentrations were depleted in the sediments in which declining milfoil plants were rooted, but declining plants showed no physiological evidence of P

Table 3
Possible Causes of Eurasian Watermilfoil Declines[1]

Nutrient depletion
Toxin accumulation
Shading by phytoplankton or attached algae
Parasite(s) or pathogens(s)
Harvesting/herbicides
Climatic fluctuations
Competition from other macrophytes
Insect herbivory (Painter and McCabe 1988)

[1] After Carpenter (1980) except as noted.

limitation (Smith 1979). A recent study has identified nitrogen (N) as more limiting than P for *M. spicatum* growth (Anderson and Kalff 1986). The possibility that N depletion from sediments contributes to declines has not been adequately investigated (Barko, Gunnison, and Carpenter, in press). Other sediment alterations may also be important. Vigorous growth of nuisance species contributes to rapid accumulation of organic sediments. Accumulation of organic matter dilutes sediment nutrients, thereby making them less available for plant growth (Barko and Smart 1986). Organic matter from some plant species, including *M. spicatum*, may also contain materials that inhibit the growth of aquatic plants (Barko and Smart 1986).

The role of herbivores, especially insects, in limiting submersed plant growth also deserves additional study. In some cases, high densities of herbivorous insects accompany milfoil declines (Kangasniemi 1983, Painter and McCabe 1988). Several insects may be important, including a caddisfly, several moths, several weevils, and one or more chironomid species. Even if herbivorous insects alone cannot control the growth of nuisance submersed plants, they may be very important when other factors slow plant growth.

Whatever the causes of *M. spicatum* declines, there is some evidence that intense management may prolong its dominance. Carpenter (1980) reported that luxuriant growths of *M. spicatum* persisted in frequently harvested areas of Lake Wingra long after the species had declined elsewhere in the lake.

In two additional well-documented cases in which *M. spicatum* did not decline after 10 or more years (i.e. the upper TVA reservoirs and the Okanagan area lakes), the lakes were more intensely managed than those where declines were recorded (Table 4). Although disturbance appears to favor invasion by *M. spicatum*, it is not clear why management would permit its continued dominance. Thus, research on the long-term effects of aquatic plant management is needed.

Table 4
Apparent Relationship Between Management and Eurasian Watermilfoil Persistence (Smith and Barko 1990)

Location	Management Technique (s)	Approx. Percentage of Milfoil Affected	Decline
Chesapeake Bay	None	~0	Yes
Lake Wingra	Harvesting	<5	Yes
Devil's Lake, Wisconsin	None	0	Yes
Guntersville Reservoir	Herbicides Drawdown	7 100	No
Okanagan Lake	Many	18	Locally
Cultus Lake	Rototilling	33	No
Shuswap Lake	Many	44	No

Future Directions

The key to ecologically sound aquatic plant management is the identification of factors promoting success of exotic plant invasions and those that cause natural declines. Observation of ongoing invasions and declines, combined with field and laboratory experimentation, can pinpoint these controlling factors and the mechanisms by which they operate. It will then be possible to identify conditions under which management is most necessary, when management is most likely to succeed, or when specific management techniques are likely to be counterproductive. Development of management strategies that hasten natural declines may also be possible.

References

Anderson, M. R., and Kalff, J. 1986. Nutrient limitation of *Myriophyllum spicatum* growth in situ. *Freshwat. Biol.* 16:735-743.

Barko, J. W., and Smart, R. M. 1986. Sediment-related mechanisms of growth limitation in submersed macrophytes. *Ecology* 67:1328-1340.

Barko, J. W., Gunnison, D., and Carpenter, S. R. Sediment interactions with submersed macrophyte growth and community dynamics. *Aquat. Bot.*, in press.

Baumann, P. C., Kitchell, J. F., Magnuson, J. J., and Kayes, R. B. 1974. Lake Wingra, 1837-1973. A case history of human impact. *Wisconsin Acad. Sci. Arts Lett.* 62:57-94.

Carpenter, S. R. 1980. The decline of *Myriophyllum spicatum* in a eutrophic Wisconsin lake. *Can. J. Bot. 58:527-535.*

Grime, J. P. 1979. *Plant Strategies and Vegetation Processes.* Wiley, New York.

Gustafson, T. D., and Adams, M. S. 1973. The remote sensing of aquatic macrophytes. Report No. 24. University of Wisconsin Madison, Institute for Environmental Studies Remote Sensing Program, Madison, WI.

Johnstone, I. M., Coffey, B. T., and Howard-Williams, C. 1985. The role of recreational boat traffic in interlake dispersal of macrophytes: A New Zealand case study. *J. Environ. Manage.* 20:263-279.

Kangasniemi, B. J. 1983. Observations on herbivorous insects that feed on *Myriophyllum spicatum* in British Columbia. Pages 214-218 in J. Taggart, ed. *Lake Restoration, Protection, and Management*, Proceedings Second Annual Conference, North American Lake Management Society, October 1982, Vancouver, BC. US Environmental Protection Agency, Washington, DC.

Keast, A. 1984. The introduced aquatic macrophyte, *Myriophyllum spicatum*, as habitat for fish and their invertebrate prey. *Can. J. Zool.* 62:1289-1303.

Lillie, R. A. 1986. The spread of Eurasian watermilfoil *Myriophyllum spicatum* in Davis Lake, Sauk County, Wisconsin. *Lake and Reservoir Manage.* 2:64-68.

Lind, C. T., and Cottam, G. 1969. The submerged aquatics of University Bay: A study in eutrophication. *Amer. Midl. Natur.* 81:353-369.

Madsen, J. D., Sutherland, J. W., Bloomfield, J. A., and Roy, K. 1989. The Lake George aquatic plant survey. Lake George Park Commision Final Report. New York State Department of Environmental Conservation, Albany, NY.

Newroth, P. R. 1985. A review of Eurasian watermilfoil impacts and management in British Columbia. Pages 139-153 in L. W. J. Anderson, ed. *Proceedings of the First International Symposium on the Watermilfoil (Myriophyllum spicatum) and Related Haloragaceae Species.* Aquat. Plant Manage. Soc., Washington, DC.

Nichols, S. A., and Mori, S. 1971. The littoral macrophyte vegetation of Lake Wingra. *Trans. Wis Acad. Sci. Arts Lett.* 59:107-119.

Painter, D. S., and McCabe, K. J. 1988. Investigation into the disappearance of Eurasian watermilfoil from the Kawartha Lakes. *J. Aquat. Plant Manage.* 26:3-12.

Smith, C. S. 1979. Phosphorus and nitrogen content and uptake by macrophytes. Pages 33-42 in J. E. Breck et al., eds. *Aquatic Plants, Lake Management, and Ecosystem Consequences of Lake Harvesting*. Proc. Conf. Institute for Environmental Studies, Univ. Wisconsin-Madison, Madison, WI.

Smith, C. S., and Barko, J. W. 1990. Ecology of Eurasian watermilfoil. *J. Aquat. Plant Manage*. 28:55-64.

Effects of Benthic Barriers on Aquatic Habitat: Preliminary Results

by
Harry L. Eakin[1]

Introduction

In many of our Nation's lakes, reservoirs, streams, and estuaries, extensive beds of submersed aquatic vegetation have resulted, in some instances, in reduced public access to boat launching ramps, docks, channels, and swimming areas. Currently, the predominant management strategies employed to maintain accessibility to these areas include the use of herbicides and/or mechanical harvesting. A possible alternative management strategy, particularly suitable to small treatment areas, is the use of benthic barriers (Figure 1).

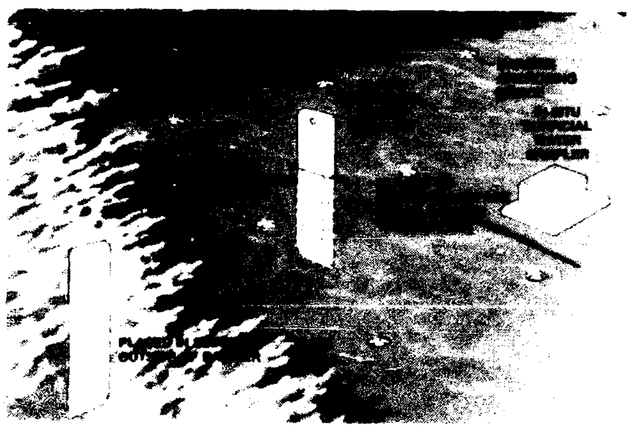


Figure 1. Benthic barrier

Benthic barriers placed securely upon the sediment surface can effectively curtail aquatic plant growth for several growing seasons. Control is achieved by physically blocking the plants' access to the water column and by eliminating any light from reaching the plants. Although the use of benthic barriers is increasing, information concerning their effects on the aquatic habitat remains sparse. Therefore, investigations designed to examine influences of barrier placement on underlying sediment, surficial water beneath barriers, and benthic fauna have been initiated at Lake Guntersville, Alabama; Eau Galle Reservoir, Wisconsin; and the Lewisville Aquatic Ecosystem Research Facility, Texas.

Materials and Methods

Benthic barriers selected for use in these investigations are commercially available from Dow-Corning Corporation, Midland, MI, under the trade name Bottom-Line, and consisted of separate 20- by 40-ft mats. Installation of the barriers was in accordance with manufacturer's suggested methods and required the use of scuba (Photos 1 and 2). Barrier mats were deployed in August 1989 at Eau Galle Reservoir and in June and July 1990 at Lake Guntersville and the Lewisville Facility, respectively. Two barriers were deployed in both Eau Galle Reservoir and the Lewisville Facility. Five barriers were installed in Lake Guntersville at separate sites.

Photo 1. Deployment of benthic barrier

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Photo 2. Installation of barrier anchoring devices

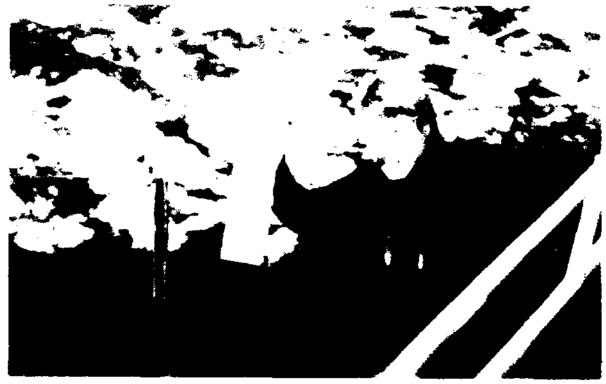


Photo 3. Sampling of interstitial water

Collection of samples for analysis of selected parameters (Table 1) was initiated during 1990 at each location. Samples included cores of the upper 10 cm of sediment, interstitial water (Photo 3), and surficial water from beneath the barriers. Sediment cores were taken using standard coring techniques. Sampling of the interstitial water and surficial water utilized two types of in situ dialysis chambers (Figure 2). Interstitial water samples were deployed vertically in sediment beneath and outside the barriers to determine if changes in concentrations of selected chemical constituents might result from barrier placement. Water from the surficial in situ chambers was analyzed to determine its oxygen status and concentrations of selected chemical constituents.

Table 1
Selected Physical and Chemical Parameters

Sample Type	Selected Parameter
Sediment core	Moisture
	Density
	Organic content
	Exchangeable ammonium nitrogen
	Exchangeable potassium
	Available phosphate phosphorus
	Available iron
	Available manganese
	Total nitrogen
	Total phosphorus
	Total iron
	Total manganese
	Chemical oxygen demand
	Particle size
Interstitial water	Ammonium nitrogen
	Soluble reactive phosphorus
	Dissolved iron
	Dissolved manganese
Surficial water	Ammonium nitrogen
	Soluble reactive phosphorus
	Nitrate+nitrite nitrogen
	Dissolved iron
	Dissolved manganese

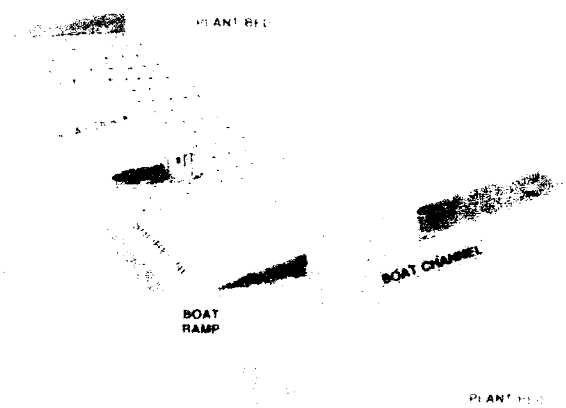


Figure 2. In situ dialysis chambers

Results and Discussion

Information from these continuing investigations, although very preliminary, has shown that the placement of benthic barriers within beds of submersed aquatic plants can create changes in the aquatic habitat beneath the barriers.

Examination of the oxygen status of water beneath the barriers at Eau Galle Reservoir showed it to be essentially anaerobic. Increased concentrations of ammonium-nitrogen and dissolved iron and manganese in the water beneath the barriers compared to the water at the sediment-water interface outside

the barriers were evident. These trends suggest that benthic invertebrates may have difficulties surviving beneath benthic barriers in some locations.

Mean dissolved oxygen concentration, approximately 4.8 mg/L, measured in the surficial water beneath the barriers in Lake Guntersville was greater than the mean concentration measured in Eau Galle Reservoir. In addition, there were no significant differences between concentrations of selected chemical constituents between samples taken beneath and outside the barriers in Lake Guntersville. Differences between these two locations might be attributed to the period of barrier installation, being approximately 10 months greater at Eau Galle than at Guntersville.

Future Research

Collection of data at each location will continue during 1991. Further examination of expanded selected physical and chemical parameters will provide an assessment of effects of benthic barriers on the aquatic habitat. This information will be of value in determining the overall utility of benthic barrier placement for the control of submersed aquatic vegetation in aquatic systems.

Preliminary Observations on the Influences of Initial Tuber Mass of Growth Responses of *Hydrilla verticillata* (L.f.) Royle

by
D. G. McFarland[1]

Introduction

Ecological studies of terrestrial plants have long shown that propagule (i.e., seed) mass influences various facets of plant growth, fitness, and survivorship (Black 1956, 1957; Harper and Obeid 1967; Wulff 1973, 1986a, 1986b; Melzack and Watts 1982; Peters 1985). Only recently, however, have similar studies been conducted with submersed aquatic vegetation. Experiments of Spencer (1986) demonstrated initial tuber mass to be closely related to the biomass production and morphology of the widely distributed pondweed *Potamogeton pectinatus* L. For many submersed plant species, tubers or subterranean turions provide an important means of population establishment and regrowth. Variations in the mass of these propagules are thought to potentially influence postgermination vigor and competitiveness of tuber-producing submersed plant populations (Spencer et al. 1987).

Hydrilla verticillata (L.f.) Royle, the exotic submersed plant species examined in the present study, is well documented for its nuisance growth in many lakes and reservoirs (Blackburn et al. 1969, Haller 1976, Steward et al. 1984). Tubers produced by this species pose serious problems for aquatic plant management due to their resistance to adverse environmental conditions, including herbicide treatment (Bruner and Batterson 1984, Steward and Van 1987). While influences of various tuber characteristics on the success of *Hydrilla* are not well known, tuber size (based on length determinations) has been linked with germination potential in this species (Haller, Miller, and Garrard 1976).

In the present study, influences of tuber mass on initial stages of development in *Hydrilla* are examined. Results reported here are intended to provide insight into the role of tuber mass in determining growth characteristics of this species, and related implications for aquatic plant management.

Methods and Materials

The study was conducted in three 1,200-L white fiberglass tanks housed in an Environmental Laboratory greenhouse, at the Waterways Experiment Station. The tanks were filled (83 cm deep) with a low-alkalinity culture solution (described in Smart and Barko 1985) that contained major nutrients, except nitrogen and phosphorus, to minimize algal growth inside the tanks. One liquid circulator per tank provided continuous water circulation and temperature control at approximately 25° C. The solution was aerated with humidified air, facilitating further mixing and increased CO_2 supply. Maximum midday photosynthetically active radiation levels averaged about 500 $\mu E/m^2/sec$ using a neutral-density shade fabric over the roof of the greenhouse that reduced natural irradiance by 75 percent.

Hydrilla tubers were obtained from 2-month-old monoecious plants established from the Laboratory's Potomac River stock culture. In an effort to maximize germination, the propagules were chilled continuously at

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

6° C (in the dark) for approximately 4 weeks prior to the initiation of the study (cf. Carter, Rybicki, and Schulman 1987). Following cold exposure, the tubers were separated by fresh weight into three classes: small (S), 100 to 150 mg; medium (M), 200 to 250 mg; and large (L), 300 to 350 mg. The propagules were planted singly in 1-L containers of well-mixed inorganic sediment from Brown's Lake, Mississippi (characterized in Barko and Smart 1986). One weight class was assigned per tank, with 50 replicate containers held in each. Ten replicates of each tuber class were removed for harvests at weeks 1, 2, 3, 4, and 6.

Evaluations of the growth of individual plants were based on determinations of dry shoot and root biomass, maximum shoot and root lengths, and numbers of shoots and shoot apices. Statistical analyses of all data were performed using analysis of variance procedures of the Statistical Analysis System (SAS Institute, Cary, NC). Hereafter, statements of statistical significance refer to probability levels of 0.05 or less.

Preliminary Results

Results of the Duncan's Multiple Range Test used to contrast weekly growth responses among the three tuber classes indicated that, in most cases, significant variations in growth were effected by initial tuber mass within the first 4 weeks of the study. Because responses among the three tuber classes were quite similar by week 6, data reported here reflect determinations obtained for weeks 1 through 4 only.

Shoot and root biomass

Significant effects of tuber mass on shoot production occurred during the first two weeks, when plants emerging from L (large) and M tubers exhibited greater shoot biomass than those from S tubers (Figure 1). Root production was unresponsive to tuber mass in the first week. However, by week 2, the biomass of roots in the L tuber class exceeded that in the smaller tuber classes. Beyond the initial 2-week period, effects of tuber mass on both shoot and root production were relatively minor.

Shoot and root length

The lengths of roots and shoots were initially least in the L tuber class (Figure 2). After the first week, however, shoots from L tubers were generally longer than those from either M or S tubers. Likewise by week 3, the length of roots in the L tuber class exceeded the lengths of roots in the two smaller classes. By week 4, differences in root length among the three tuber classes were negligible.

Numbers of shoots and apices

There were no significant effects of tuber mass on the numbers of shoots produced (Figure 3). Statistically different branching responses among the three tuber groups were detected at weeks 3 and 4, as apices formed by individual plants were most abundant in the L tuber class.

Conclusions and Recommendations for Future Research

Results of this investigation indicate that tuber mass is an important factor determining initial growth patterns in *Hydrilla*. Data reported here showed shoot elongation, branching, and initial biomass accrual to be most vigorous in plants germinated from large tubers. Such differences in growth effected by tuber mass could have adaptive significance in responses of *Hydrilla* to environmental gradients. Furthermore, variations in growth imposed by tuber mass might influence the outcome of both intraspecific and interspecific competition involving this species.

Recently, Spencer et al. (1987) quantified variations in tuber mass of *Hydrilla* populations grown under natural and seminatural conditions. The asymmetrical distributions of tuber mass in those populations suggest possible selection for or against propagules with certain physiological properties. It is

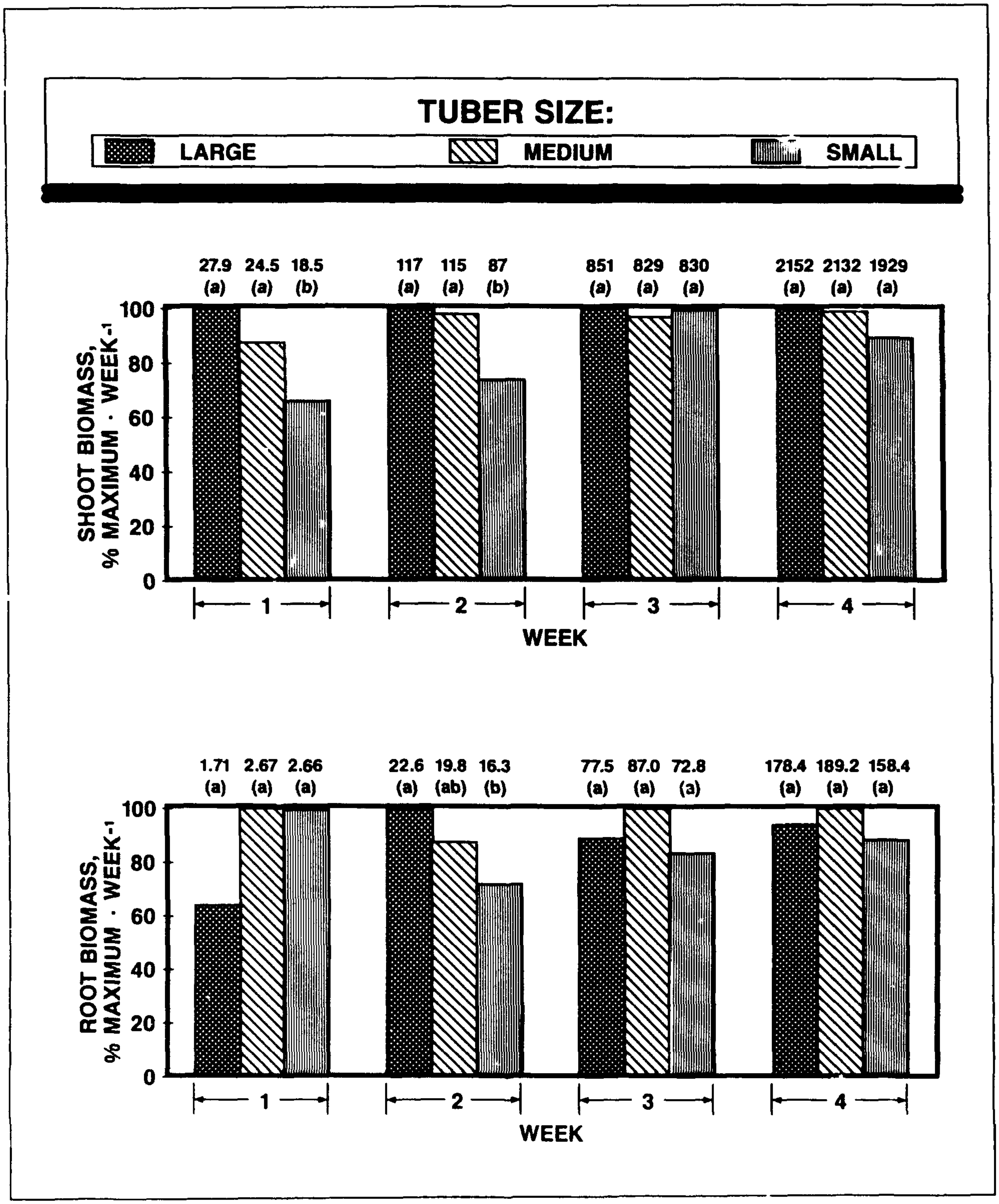


Figure 1. Weekly shoot and root biomass of Hydrilla grown from large, medium, and small tubers. Within each subfigure, biomass is expressed as a percentage (from 0 to 100 percent) of the maximum mean per week. Numbers above bars indicate actual mean determinations ($n = 10$) in milligrams dry mass. For each week, mean shoot or root biomass values sharing the same letter do not differ significantly from each other. Duncan's Multiple Range Test was used to determine statistical significance at $P < 0.05$

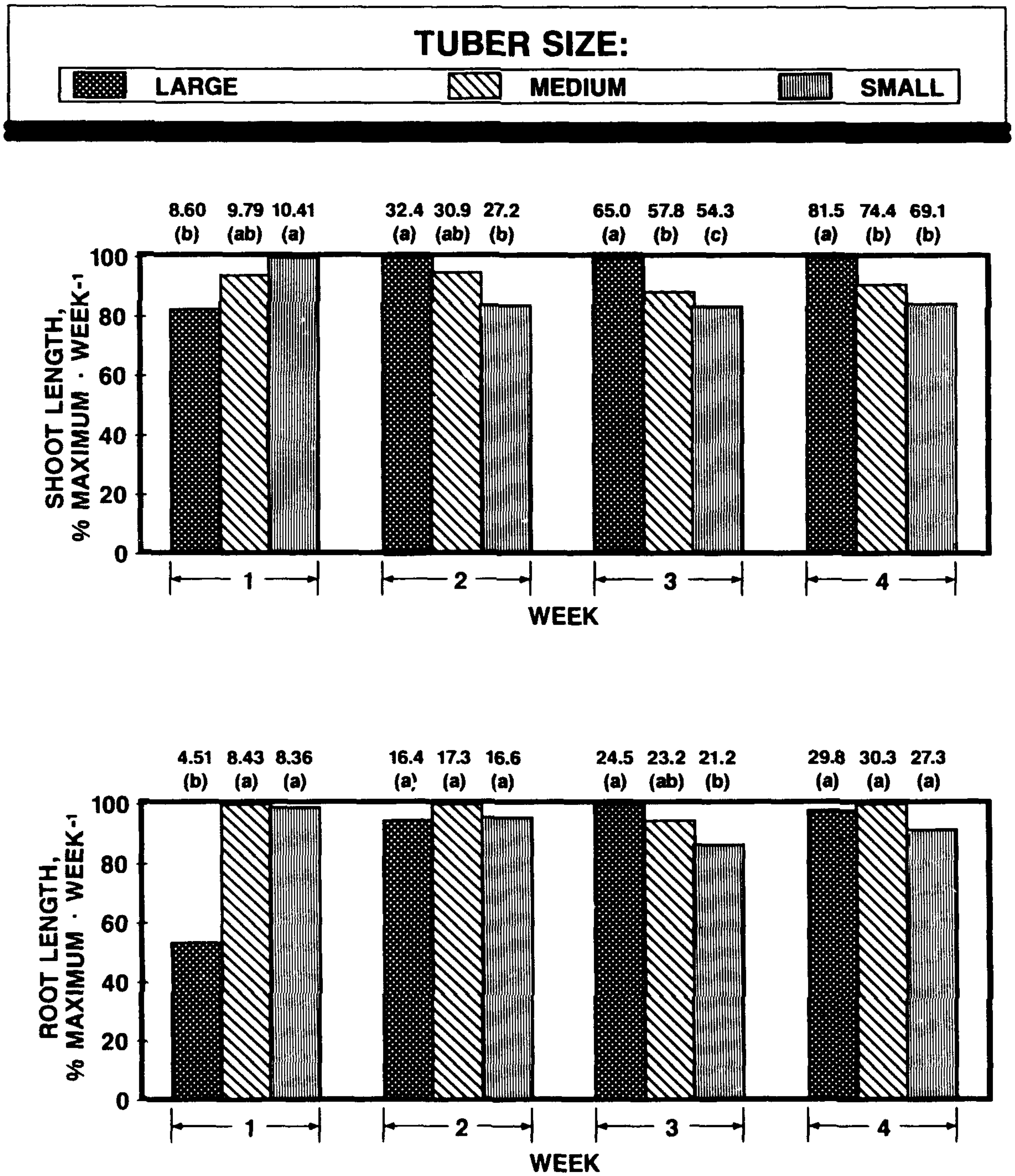


Figure 2. Weekly shoot and root lengths of Hydrilla grown from large, medium, and small tubers. Within each subfigure, length is expressed as a percentage (from 0 to 100 percent) of the maximum mean per week. Numbers above bars indicate actual mean determinations ($n = 10$) in centimeters. For each week, mean shoot or root lengths sharing the same letter do not differ significantly from each other. Duncan's Multiple Range Test was used to determine statistical significance at $P < 0.05$

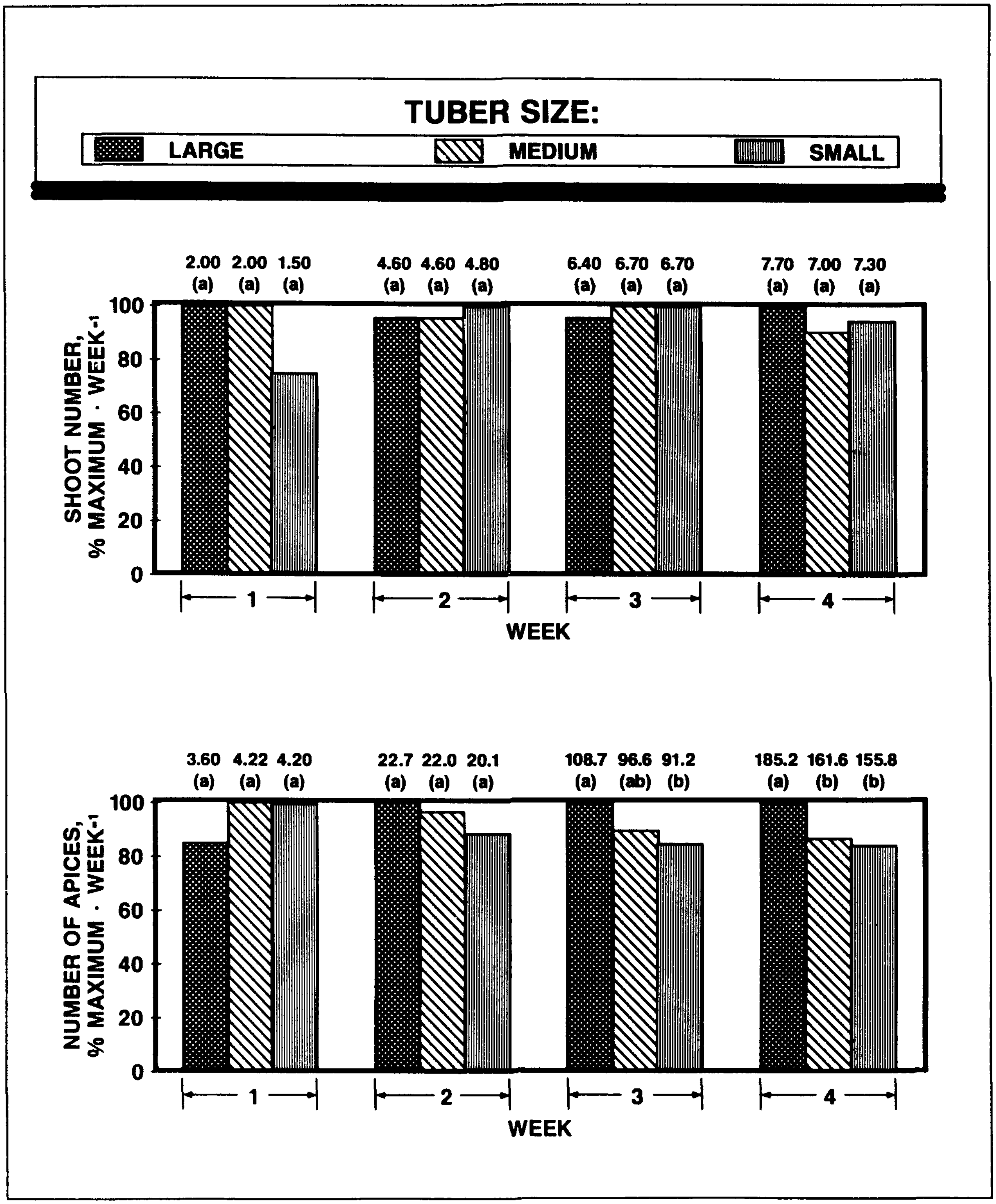


Figure 3. Weekly numbers of shoots and apices of Hydrilla grown from large, medium, and small tubers. Within each subfigure, these numbers are expressed as a percentage (from 0 to 100 percent) of the maximum mean per week. Numbers above bars indicate actual mean determinations (n = 10) based on direct counts. For each week, mean numbers of shoots or apices sharing the same letter do not differ significantly from each other. Duncan's Multiple Range Test was used to determine statistical significance at $P < 0.05$

recommended, therefore, that laboratory investigations be conducted to further elucidate environmental factors potentially regulating biomass accumulation and growth of tubers (and other propagules) of *Hydrilla*. Results of these investigations could be beneficial in the development of environmental manipulations to select for inferior propagule and plant formation.

Finally, future studies are recommended to examine growth potential relative to propagule (tuber) mass in other important aquatic plant species as well (for example, *Potamogeton nodosus* Poiret and *Vallisneria americana* (Michx.). This information may prove helpful in the selection of propagules used in planting programs to establish native nonweedy vegetation, especially in efforts to deter the spread of nuisance submersed plant species such as *Hydrilla*.

Acknowledgments

The author gratefully acknowledges F. Ashley Boyd, Wanda A. Dee, Monica M. Humphrey, and Deborah K. Northam for their technical assistance in the conduct of this study. Appreciation is also extended to Dr. John W. Barko for his helpful comments in the review of this manuscript. Support for this investigation was provided by the US Army Corps of Engineers Aquatic Plant Control Research Program.

References

Barko, J. W., and Smart, R. M. 1986. "Effects of Sediment Composition on Growth of Submersed Aquatic Vegetation," Technical Report A-86-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS

Black, J. N. 1956. "The Influence of Seed Size and Depth of Sowing on Preemergence and Early Vegetative Growth of Subterranean Clover (*Trifolium subterraneum* L.)," *Australian Journal of Agricultural Research*, Vol 7, pp 98-109.

Black, J. N. 1957. "The Early Vegetative Growth of Three Strains of Subterranean Clover (*Trifolium subterraneum* L.) in Relation to Size of Seed," *Australian Journal of Agricultural Research*, Vol 8, pp 1-14.

Blackburn, R. D., Weldon, R. W., Yeo, R. R., and Taylor, T. M. 1969. Identification and Distribution of Certain Similar-Appearing Submersed Aquatic Weeds in Florida," *Hyacinth Control Journal*, Vol 8, pp 17-21.

Bruner, M. C., and Batterson, T. R. 1984. "The Effect of Three Sediment Types on Tuber Production in Hydrilla [*Hydrilla verticillata* (L.f.) Royle]," *Journal of Aquatic Plant Management*, Vol 22, pp 95-97.

Carter, V., Rybicki, N. B., and Schulman, C. L. 1987. "Effects of Salinity and Temperature on Germination of Monoecious Hydrilla Propagules," *Journal of Aquatic Plant Management*, Vol 25, pp 54-57.

Haller, W. T. 1976. "*Hydrilla:* A New and Rapidly Spreading Aquatic Weed Problem," Circular S-245, Agricultural Experiment Station, IFAS, University of Florida, Gainesville, FL.

Haller, W. T., Miller, J. L., and Garrard, L. A. 1976. "Seasonal Production and Germination of Hydrilla Vegetative Propagules," *Journal of Aquatic Plant Management*, Vol 14, pp 26-28.

Harper, J. L., and Obeid, M. 1967. "Influence of Seed Size and Depth of Sowing on the Establishment and Growth of Varieties of Fiber and Oilseed Flax," *Crop Science*, Vol 7, pp 527-532.

Melzack, R. N., and Watts, D. 1982. "Variation in Seed Weight, Germination, and Seedling Vigour in the Yew (*Taxus baccata* L.) in England," *Journal of Biogeography*, Vol 9, pp 55-63.

Peters, N. C. B. 1985. "Competitive Effects of *Avena fatua* L. Plants Derived from Seeds of Different Weights," *Weed Research*, Vol 25, pp 67-77.

Smart, R. M., and Barko, J. W. 1985. "Laboratory Culture of Submersed Freshwater Macrophytes on Natural Sediments," *Aquatic Botany*, Vol 21, pp 251-263.

Spencer, D. F. 1986. "Tuber Demography and Its Consequences for *Potamogeton pectinatus* L.," *Proceedings, 7th International Symposium on Aquatic Weeds*, European Weed Research Society, Association of Applied Biologists, pp 321-325.

Spencer, D. F., Anderson, L. W. J., Ames, M. D., and Ryan, F. J. 1987. "Variation in *Hydrilla verticillata* (L.f.) Royle Propagule Weight," *Journal of Aquatic Plant Management*, Vol 25, pp 11-14.

Steward, K. K., and Van, T. K. 1987. "Comparative Studies of Monoecious and Dioecious Hydrilla (*Hydrilla verticillata*) Biotypes," *Weed Science*, Vol 35, pp 204-210.

Steward, K. K., Van, T. K., Carter, V., and Pieterse, A. H. 1984. "Hydrilla Invades Washington, DC, and the Potomac," *American Journal of Botany*, Vol 71, pp 162-163.

Wulff, R. D. 1986a. "Seed Size Variation in *Desmodium paniculatum*; I. Factors Affecting Seed Size," *Journal of Ecology*, Vol 74, pp 87-98.

Wulff, R. D. 1986b. "Seed Size Variation in *Desmodium paniculatum;* II. Effects on Seedling Growth and Physiological Performance," *Journal of Ecology*, Vol 74, pp 99-114.

Wulff, R. D. 1973. "Intrapopulational Variation in the Germination of Seeds in *Hyptis suaveolens*," *Ecology*, Vol 54, pp 646-649.

Effects of Benthic Barriers on Macroinvertebrate Communities

by
Barry S. Payne[1] *and Thomas Ussery*[2]

Introduction

Benthic barriers are used to prevent the growth of submersed macrophytes in areas of high use such as small boat harbors and swimming areas. In most applications, these barriers are placed at sites where control is needed prior to the onset of rapid shoot growth in late spring and early summer. The barriers are held in place by an array of pins driven through the barrier and into the underlying substrate. The barriers block light needed for shoot growth, and also present a physical barrier to the upward growth of shoots.

Studies are being conducted to evaluate the physical and chemical effects of barriers on water and sediment under the barrier (Gunnison and Barko 1989) and to determine the responses of benthic macroinvertebrate communities. This paper reports on effects of experimental placement of barriers on benthic macroinvertebrate communities in Eau Galle Reservoir (EGL), Wisconsin; Guntersville Reservoir (GUN), Alabama; and ponds in north-central Texas at the Lewisville Aquatic Ecosystem Research Facility (LEW) of the Waterways Experiment Station.

Methods

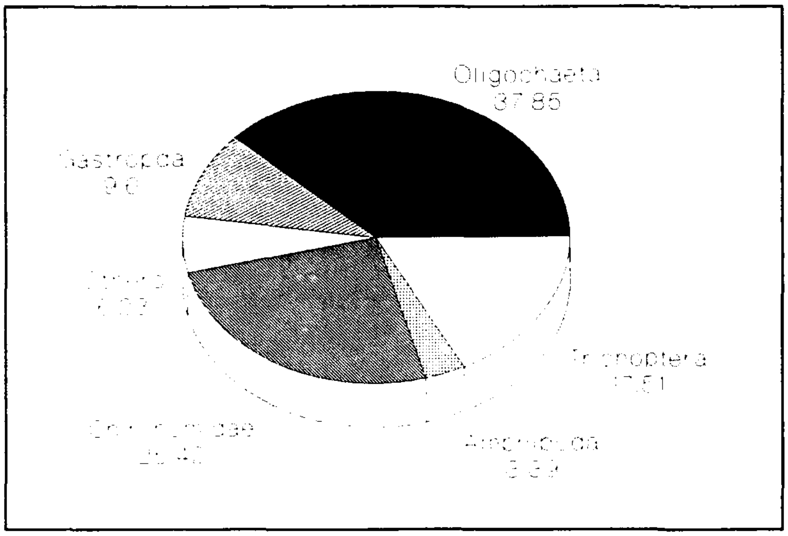
Barriers measuring 6.1 by 6.1 m were placed over areas with dense submersed macrophytes in late spring to early summer at all locations. Water depths ranged from 1.5 to 3 m at the specific locations of barrier placement. Four barriers were placed at LEW, two at GUN, and two at EGL. Core samples of sediments including macroinvertebrates (Miller and Bingham 1987) were obtained at sites of barrier placement and adjacent reference areas (dense plants, no barrier) just prior to and after placement of barriers. Caution was taken not to include live plant shoots in these samples. Typically, five samples were obtained from beneath each barrier and each adjacent reference site on each date of sampling. Greater than 95 percent of all macroinvertebrates were restricted to the upper 10 cm of sediment. Thus, only the top 10 cm of sediment was routinely analyzed. Sediments were washed through a 0.5-mm sieve, and all macroinvertebrates were picked from material retained on the sieve. Invertebrates were enumerated by major taxa, and the total number of individuals per square meter was estimated from these counts per core sample.

No significant differences (Student's t-test, $p < 0.05$) were noted in macroinvertebrate density between each pair of barrier and reference sites at each location. In addition, differences between the multiple barrier or reference sites at each location were generally not significant. Thus, density estimates were pooled per location for all samples per date obtained below barriers and all samples per date obtained from reference sites.

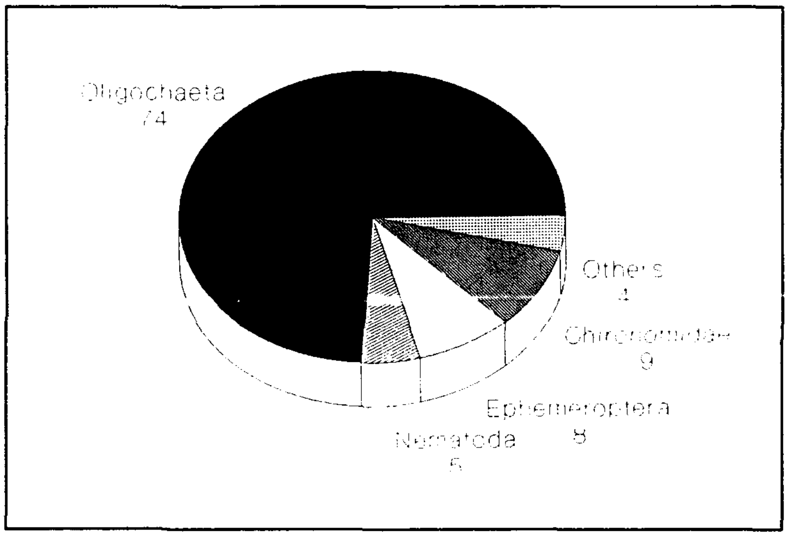
Results

Oligochaetes and chironomids were among the most abundant taxa at all three locations (Figure 1). At EGL, the macroinvertebrate community of the reference sites was dominated by oligochaetes (38 percent), chironomids (25 percent), trichopterans (18 percent),

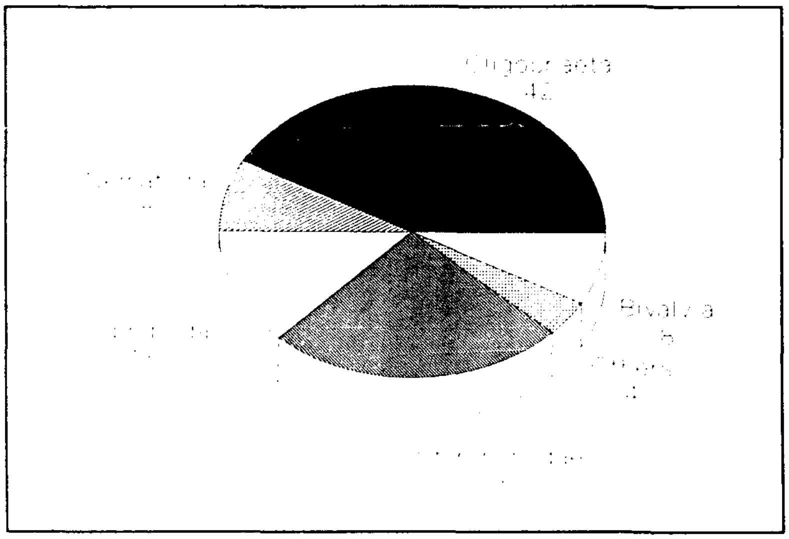
[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] University of Texas at Arlington, Department of Biology, Arlington, TX.



a. Eau Galle Reservoir



b. Lewisville ponds



c. Guntersville Reservoir

Figure 1. Relative abundance (percent) of dominant invertebrates in reference site sediments

and gastropods (10 percent). At LEW, oligochaetes (74 percent) were heavily dominant. Chironomids, the second most abundant taxon at LEW, comprised only 9 percent of the community. At GUN, chironomids (42 percent), oligochaetes (25 percent), and amphipods (13 percent) were dominant.

Significant reduction of macroinvertebrate density was observed under barriers at all locations (Figure 2). At EGL, macroinvertebrate density declined from approximately 6,000 individuals per square meter to 2,000 per square meter within 2 months after barrier placement. Macroinvertebrates at GUN were less dense than at EGL; reference site density at GUN averaged less than 1,500 individuals per square meter. Approximately 2 months after mat placement, density was approximately 150 individuals per square meter. AT LEW, approximately 5,500 individuals per square meter occurred in reference sites, compared to less than 500 individuals per square meter below the barriers.

Detailed investigations at LEW showed that essentially all density reduction occurred within 1 week after barrier placement. No recovery from this density reduction was noted under the barriers for the following 4 months (Figure 3).

Summary

Aquatic weed barriers led to marked reduction (67 to 92 percent) in the density of macroinvertebrates in sediments relative to adjacent reference areas with plants but no barriers. The reduction in density occurred rapidly and was sustained throughout the growing season, based on detailed observations at one location (LEW). Studies are continuing at LEW to determine the rate of recovery after barriers are removed.

Aquatic weed barriers are highly effective at prevention of plant growth, but elimination of most benthic macroinvertebrates may be anticipated directly under the barriers. The small surface area affected by barriers relative to the total littoral zone of most lakes and reservoirs where barriers are used reduces the system-wide importance of these local losses of benthic production.

References

Gunnison, D., and Barko, J. 1989. "Effects of Benthic Barriers on Substratum Conditions," *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-89-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp 175-177.

Miller, A. C., and Bingham, C. R. 1987. "A Hand-Held Benthic Core Sampler," *Journal of Freshwater Ecology,* Vol 4, pp 77-81.

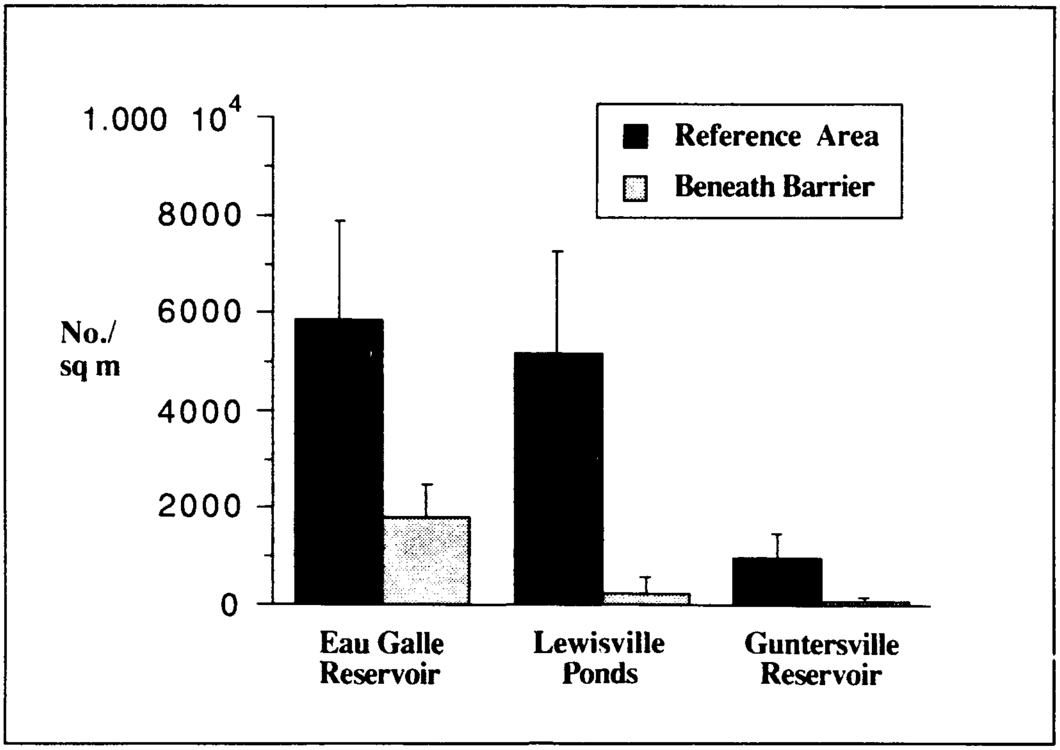


Figure 2. Comparison of macroinvertebrate density beneath barriers and in adjacent reference sites

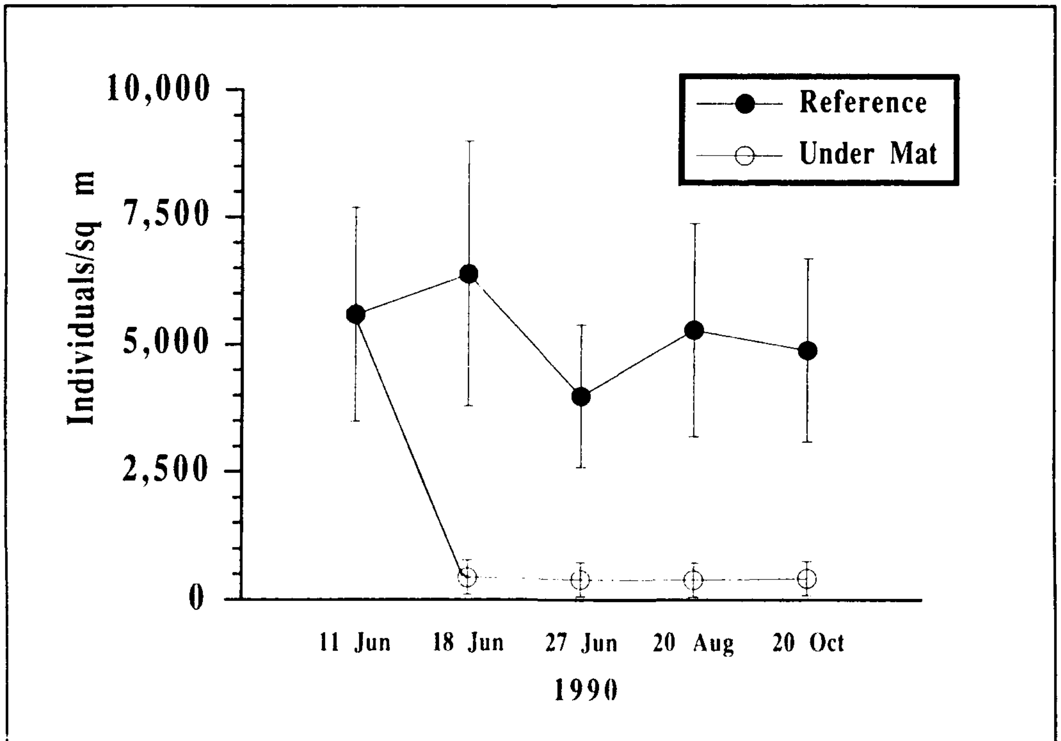


Figure 3. Comparison of macroinvertebrate density beneath barriers and in reference sites at Lewisville from date of placement through end of growing season

Biological Control of Aquatic Plants

A History and Overview of Biocontrol Technology

by
Alfred F. Cofrancesco, Jr.[1]

Technology Development

The development of biocontrol technology began in 1959 when the US Army Corps of Engineers and the US Department of Agriculture (USDA) entered into a cooperative study to manage exotic aquatic plants. In the first attempt, classical biological approaches were used. Researchers traveled to the country of origin of the plant and looked for natural enemies.

The first plant targeted for research with biocontrol technology was alligatorweed (*Alternanthera philoxeroides*), a native of South America. This plant species grows primarily as an emersed aquatic plant rooted to bottom soils, with the major portion of the plant foliage growing above water. However, the plant can also grow in terrestrial habitat (Godfrey and Wooten 1979). In aquatic systems the plant would produce large mats composed of hollow plant stems that would severely impact the use of the waterway.

In 1960, a USDA Laboratory was established in Argentina as part of the cooperative effort of the USDA and the Corps of Engineers to develop biocontrol agents for alligatorweed (Coulson 1977). During the initial surveys, over 40 insects that feed on alligatorweed were found. As testing progressed, the number of potential agents was reduced to five insects (Vogt 1960). Additional testing reduced the number of possible insect biocontrol agents to three, and all were petitioned for release.

The first insect released was the alligatorweed flea beetle (*Agasicles hygrophila*). In 1964, initial releases were made in California and South Carolina (Coulson 1977, Cofrancesco 1988). This insect has a short life cycle of 30 days, and both the adults and larvae feed on alligatorweed. The impact to populations of alligatorweed by this insect occurred rapidly, and the insect was eventually released in 11 states (Cofrancesco 1988).

The next insect released in the United States as a biocontrol agent of alligatorweed was the alligatorweed thrips (*Amynothrips andersoni*). Initial releases were made in 1967 in California, South Carolina, Florida, and Georgia (Coulson 1977). This insect has a life cycle of approximately 28 days (Maddox and Mayfield 1979). Both adults and larvae of this insect feed on the plant with their sucking mouth parts, which causes the alligatorweed leaves to dry and curl. The impact of this agent has not been widespread throughout the United States, even though it was released in seven states (Cofrancesco 1988).

The last insect biocontrol agent released for alligatorweed was the alligatorweed stem borer (*Vogtia malloi*). The first releases of this insect were made in 1971 in Florida, Georgia, North Carolina, and South Carolina. The insect's life cycle is approximately 39 days, and only the larvae feed on the plant. The feeding process begins at the apical portion of the plant, where the larvae hatch and bore into the hollow stem (US Army Engineer Waterways Experiment Station 1981). The impact caused by this insect is significant, especially in the northern range of alligatorweed. This insect was released in only five states; however, in a 1981 survey it was found widely distributed in seven states (Cofrancesco 1988).

In 1963, there were over 97,000 problem acres of alligatorweed in the United States;

---

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

in 1981, there were less than 1,000 problem acres of alligatorweed (Cofrancesco 1988). Currently, only North Carolina has a small program to treat alligatorweed with herbicides in ditches. All the other states rely on biocontrol agents to maintain the population level of alligatorweed below problem levels.

The second plant targeted for biocontrol technology was waterhyacinth (*Eichhornia crassipes* Mart. (Solms)), an aggressive floating plant species native to South America. Waterhyacinth was introduced into the United States at the 1884 Cotton States Exposition in New Orleans, LA (Sanders, Theriot, and Perfetti 1985). Since its introduction, waterhyacinth has spread or been distributed throughout the southern United States and California (Godfrey and Wooten 1979). The ability of waterhyacinth to infest a wide range of freshwater habitats and its tremendous growth rate (Penfound and Earle 1948, Center and Spencer 1981) have made it one of the most troublesome aquatic plants in the United States.

Overseas surveys were conducted in South America to find potential biocontrol agents of waterhyacinth. A number of insects were found that feed on waterhyacinth in its native range, and studies were initiated to determine which insects would be good biocontrol agents. These studies were conducted at the USDA Laboratory in Argentina. Three potential insect biocontrol agents were identified, and introduction permits were requested (Sanders, Theriot, and Perfetti 1985).

In 1972 the mottled waterhyacinth weevil (*Neochetina eichhornia*) was the first insect approved for release as a biocontrol agent of waterhyacinth. The initial releases were conducted in Florida; however, this insect has now been released in four other states. Both the adults and the larvae feed on the plant. Adults remove the upper leaf surface, and larvae penetrate the petiole and feed on internal tissues. As the larva grows, feeding proceeds down the petiole to the plant crown (Sanders, Theriot, and Perfetti 1985). The generation time ranges from 90 to 120 days depending on temperature and other factors (DeLoach and Cordo 1976a). These insects stress the plant; however, their true impact to the plant population takes years to become apparent.

The second biocontrol agent released on waterhyacinth was another weevil, the chevroned waterhyacinth weevil (*Neochetina bruchi*). The first release of this insect occurred in Florida in 1974 (Sanders, Theriot, and Perfetti 1985). The chevroned waterhyacinth weevil occupies very similar habitats in the plant as does the mottled waterhyacinth weevil, and its impact to the plant is similar. The chevroned waterhyacinth weevil has a shorter generation time (60 to 90 days) than the mottled waterhyacinth weevil (Deloach and Cordo 1976b).

The last biocontrol agent released on waterhyacinth in the United States was the argentine waterhyacinth moth (*Sameodes albiguttalis*) native to South America. Its initial release was made in Florida in 1977. This insect has a life cycle of approximately 30 days (Deloach and Cordo 1978, Center 1981a). The larvae are the only life stage that feeds on the plant, and they are usually found on the smaller, more bulbous plants (Center 1981b). The impact caused by these insects varies among sites; often, well-established populations of these insects will move from locations for no apparent reason (Sanders, Theriot, and Perfetti 1985).

Plant pathogens were also examined as possible biocontrol agents of waterhyacinth. In 1971, a pathogen (*Cercospora rodmanii*) of waterhyacinth was found on plants in Lake Rodman, Florida, by University of Florida researchers (Conway, Freeman, and Charudattan 1974). Under a contract with the Corps of Engineers, the University tested this pathogen as a possible biocontrol agent of waterhyacinth. After laboratory testing, Abbott Laboratory was contracted to develop a commercial formulation. The first field testing of this formulation was conducted in 1975 at Lake Theriot, Louisiana. The formulation infected the plants, but the virulence of the

commercial formulation was low (Sanders, Theriot and Perfetti 1985).

In general, problem areas of waterhyacinth still exist, and chemical spray control operations continue. The biocontrol insects are having a significant impact on the waterhyacinth populations, but this is occurring in areas where the insect population levels are allowed to build. Most of the impact that has been documented has been attributed to the weevils. These insects have longer life cycles, so population buildup is slow.

Dramatic declines in the acreage of waterhyacinth have occurred in Louisiana where, prior to the insects being released, the acreage of waterhyacinth reached 1.2 million acres (Cofrancesco, Stewart, and Sanders 1985) (Figure 1). Similar declines were also noted in Florida and Texas. Although waterhyacinth problems still exist, the biocontrol agents are stressing the plants, and research is under way to develop better management procedures for these agents (Cofrancesco 1987).

Another problem aquatic plant that has been studied is waterlettuce (*Pistia stratiotes*). This plant is distributed mainly in the southeastern United States and has presented problems in areas where waterhyacinth populations are declining (Dray, Center, and Habeck 1989). In addressing this problem, we built upon work conducted by the Australians, who have had a management program for waterlettuce for a number of years.

The first insect released on waterlettuce was *Neohydronomous affinis*, a weevil native to South America that the Australians have been using since 1982 (Julien 1987). Additional testing of this insect was conducted prior to its release in 1987 in Florida (Dray et al. 1990). The adults feed and penetrate the leaf while the larvae mine inside the leaf (Thompson and Habeck 1989). The insect's life cycle is approximately 30 days, which allows its population to develop rapidly (Habeck et al. 1988). Eighteen months after the release of the weevils at a site in Lake Okeechobee, Florida, the entire 75-acre mat of waterlettuce was eliminated. Weevils began to migrate to adjacent control plots prior to the elimination of the test site (Center and Dray 1990).

Another insect, *Namangana pectinicornia*, a moth from Thailand, has been approved for release in the United States as a biocontrol of waterlettuce. The release is scheduled for

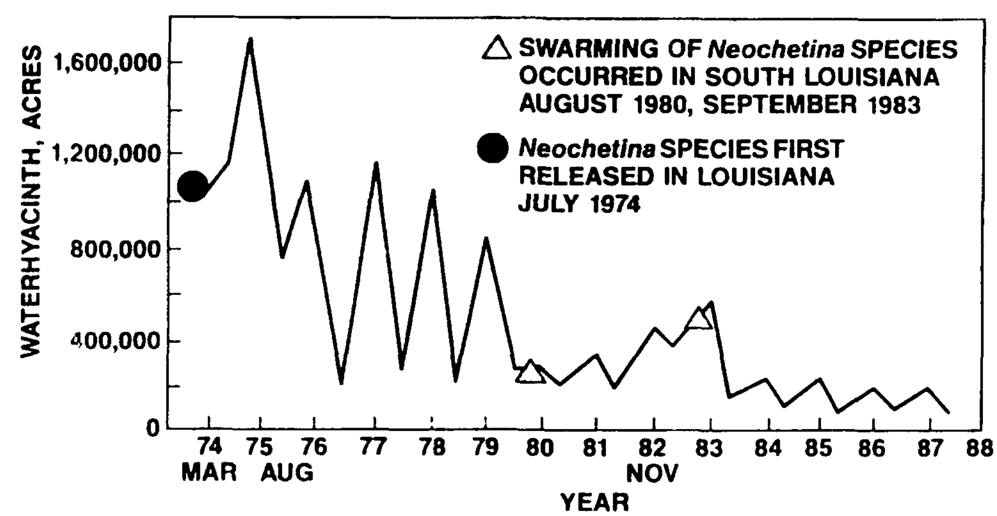


Figure 1. Total waterhyacinth acreage in Louisiana

February 1991 in Florida. This moth has a short life cycle of approximately 35 days. Only the larvae feed on the plant; however, the damage that is caused is extensive, with feeding occurring on the upper and lower leaf surface and sometimes girdling the leaves.

Biocontrol research has also been conducted on submersed aquatic plants. Research has been conducted using both insects and pathogens to manage hydrilla and Eurasian watermilfoil. Hydrilla is a submersed aquatic plant that clogs waterways and impedes navigation (Schardt and Schmidtz 1989). The plant was introduced into the United States by business, as a plant for fish aquariums. The plant has spread rapidly throughout the southern United States and along the east coast as far north as Delaware. In addition, populations of the plant are found in California.

Research began in 1980 to determine the area of origin for this problem plant. Surveys were conducted throughout Africa, Australia, and parts of Asia (Balciunas 1982, 1983, 1984, 1985, 1987; Balciunas and Dray 1985). Biocontrol agents were most abundant in India and Australia. In 1984 the USDA established a research facility in Australia with the support of the Corps of Engineers.

The first insect released on hydrilla was a weevil (*Bagous affinis*) from Pakistan. Releases were made in 1987 in Florida (Center 1989, Center and Dray 1990); however, this insect feeds on the tubers of the hydrilla plant when water recedes from the plants (Buckingham 1990). While this situation is common in Pakistan, it is very uncommon in Florida except when lakes are drained. This type of life cycle has made it difficult to establish field populations. The use of this insect is being programmed for canal systems in California that have annual periods of drawdown.

The second insect released in the United States as a biocontrol of hydrilla is *Hydrellia pakistanae*, an ephydrid fly from Pakistan. This insect was released in 1987 in Florida. The larvae mine the leaves and are the only life stage of the insect that impacts the plant (Buckingham 1990). The life cycle is short, approximately 20 days (Center and Dray 1990). Initially, problems occurred in establishing field protection; however, by mid-1990, field populations of the fly were established in Florida (Center and Dray 1990).

The third biocontrol insect released in the United States for hydrilla was *Hydrellia balciunas*, an ephydrid fly from Australia. This fly causes damage similar to that of *H. pakistanae* (Buckingham 1990). The first field release of this insect occurred in September 1989 in Broward County, Florida (Center 1990). To date, the establishment of a field population has not been verified.

Additional insect biocontrol agents are being studied as biocontrol agents of hydrilla. A weevil from Australia (*Bagous* n. sp.) is in quarantine and has been recommended for release by the Technical Advisory Group on Biocontrol. Studies are also being conducted on moth and midge larvae which are potential biocontrol agents (Center and Dray 1990).

Pathogens have also been explored as biocontrol agents of hydrilla. *Macrophomina phaseolina*, a pathogen collected in Texas, has demonstrated potential as a biological control agent for hydrilla (Joye 1990). Additional testing on host specificity and the development of a commercial formation are still needed.

Eurasian watermilfoil is the most extensive problem aquatic plant in the United States. It has been reported from over 30 states. Biocontrol research on this plant dates to 1967 with work in Yugoslavia. The major emphasis has been on pathogens to control this plant, because many of the European insects were already found in the United States.

Mycoleptodiscus terrestris was isolated from plants in western Massachusetts prior to 1979 (Gunner 1983). Testing at the University of Massachusetts, funded by the Corps of Engineers, indicated that this pathogen had

potential as a biocontrol agent of Eurasian watermilfoil. At present, ECOSCIENCE Laboratories is developing a commercial formulation of this product.

In addition to pathogen research, insects in China are being examined as possible biocontrol agents of Eurasian watermilfoil. This research began in 1989, and a number of candidates have been identified (Balciunas, Center, and Dray 1989).

Summary

Over the last 31 years, the biological control of aquatic plants has been conducted on six continents and in over 30 countries, and has involved eight overseas laboratories. To date, we have released 10 biocontrol insects on four plant species. Some or all of the insects have been established in 11 states. Five more insects are in quarantine or overseas research laboratories. Three pathogens have been identified and are at various stages of testing. In addition, 11 other countries have used the technology we have developed in biocontrol of aquatic plants.

References

Balciunas, J. K. 1982. Overseas searches for insects for control of aquatic plants. Pages 141-154 in *Proceedings, 16th Annual Aquatic Plant Control Research Program and Operations Review.* Miscellaneous Paper A-82-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1983. Overseas searches for insects on hydrilla in Southeast Asia and Australia. Pages 104-144 in *Proceedings, 17th Annual Aquatic Plant Control Research Program and Operations Review.* Miscellaneous Paper A-83-9. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1984. Overseas searches of biocontrol agents for hydrilla. Pages 78-84 in *Proceedings, 18th Annual Aquatic Plant Control Research Program.* Miscellaneous Paper A-84-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1985. Final report on the overseas survey (1981-1983) for insects to control hydrilla. Technical Report A-85-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1987. Australian insects to control hydrilla. Pages 57-66 in *Proceedings, 21st Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-87-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K., and Dray, F. A. 1985. The search for insects to control U.S. hydrilla populations. Pages 75-78 in *Proceedings, 19th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-85-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K., Center, T. D., and Dray, F. A., Jr. 1989. Testing suitability of Australian bioagents for control of *Hydrilla verticillata.* Pages 24-27 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Buckingham, G. R. 1990. Quarantine laboratory: Research for hydrilla control. Pages 34-38 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Center, T. D. 1981a. Release and establishment of *Sameodes albiguttalis* for biological control of waterhyacinth. Technical Report A-81-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Center, T. D. 1981b. *Sameodes albiguttalis,* a new biocontrol agent for waterhyacinth. *Aquatics* 3:8-12.

Center, T. D. 1989. Release and establishment of insect biocontrol of hydrilla. Papges 34-40 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Center, T. D., and Spencer, N. D. 1981. The phenology and growth of waterlettuce (*Eichhornia crassipes* [Mart.] Solms) in a eutrophic north-central Florida lake. *Aquat. Bot* 10:1-32.

Center, T. D., and Dray, F.A., Jr. 1990. Release, establishment, and evaluation of insect biocontrol agents for aquatic plant control. Pages 39-49 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cofrancesco, A. F., Jr. 1987. Influence of herbicides on weevils used as biocontrol of waterhyacinth. Paes 292-302 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cofrancesco, A. F., Jr. 1988. Alligatorweed survey of ten southern states. Miscellaneous Paper A-88-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cofrancesco, A. F., Jr., Stewart, R. M., and Sanders, D. R., Sr. 1985. The impact of *Neochetina eichhorniae* (Coleoptera: Curculionidae) on waterhyacinth in Louisiana. Pages 525-535 in *Proceedings, VI International Symposium on Biological Control of Weeds,* E. S. Delfosse, ed. Agriculture Canada, Vancouver, BC, Canada.

Conway, K. E., Freeman, T. E., and Charudattan, R. 1974. The fungal flora of waterhyacinths in Florida; Part I. Water Resources Center Publication No. 30. University of Florida, Gainesville, FL.

Coulson, J. R. 1977. Biological control of alligator weed, 1959-1972; A review and evaluation. Technical Bulletin 1547. US Department of Agriculture, Washington, DC.

DeLoach, C. J., and Cordo, H. A. 1976a. Ecological studies of *Neochetina bruchi* and *N. eichhorniae* on waterhyacinth in Argentina. *J Aquatic Plant Manage.* 14:53-59.

DeLoach, C. J., and Cordo, H. A. 1976b. Life cycle and biology of *Neochetina bruchi,* a weevil attacking waterhyacinth in Argentina, with notes on *N. eichhorniae. Ann. Entomol. Soc. Am.* 69:643-652.

DeLoach, C. J., and Cordo, H. A. 1978. Life history and ecology of the moth *Sameodes albiguttalis,* a candidate for biological control of waterhyacinth. *Environ. Entomol.* 7:309-321.

Dray, F. A., Jr., Center, T. D., and Habeck, D. H. 1989. Immature stages of the aquatic moth *Petrophila drumalis* (Lepidoptera: Pyralidae, Nymphulinae) from *Pistia stratiotes* (waterlettuce). *Florida Entomol.* 72(4):711-714.

Dray, F. A. Jr., Center, T. D., Habeck, D. H., Thompson, C. R., Cofrancesco, A. F., Jr., and Balciunas, J. K. 1990. Release and establishment in the southeastern United States of *Neohydronomus affinis* (Coleoptera: Curculionidae), an herbivore of waterlettuce (*Pistia stratiotes*). *Environ. Entomol.* 19(3):799-803.

Godfrey, R. K., and Wooten, J. W. 1979. *Aquatic and wetland plants of the southeastern United States.* The University of Georgia Press, Athens, GA.

Gunner, H. B. 1983. Microbiological control of Eurasian watermilfoil. Miscellaneous Paper A-83-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Habeck, D. H., Thompson, C. R., Dray, F. A., Center, T. D., and Balciunas, J. K. 1988. Biological control of waterlettuce. Pages 320-323 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Joye, G. F. 1990. Biocontrol of *Hydrilla verticillata* with the endemic fungus *Macrophomina phaseolina*. *Plant Disease* (Dec):1035.

Julien, M. H. 1987. *Biological control of weeds: A world catalogue of agents and their target weeds*, 2d ed. CAB International Institute of Biological Control, Wallingford, Oxon, UK.

Maddox, D. M., and Mayfield, A. 1979. Biology and life history of *Amynothrips andersoni*, a thrip for the biological control of alligatorweed. *Annals of the Entomological Society of America* 72:136-140.

Penfound, W. T., and Earle, T. T. 1948. The biology of the waterhyacinth. *Ecol. Monogr.* 18:448-472.

Sanders, D. R., Sr., Theriot, E. A., and Perfetti, P. 1985. Large-scale operations management test (LSOMT) of insects and pathogens for control of waterhyacinth in Louisiana; Vol I: Results for 1979-1981. Technical Report A-85-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schardt, J. D., and Schmidtz, D. C. 1989. 1989 Florida aquatic plant survey. Technical Report 90-CGA. Florida Dept. Natural Resources, Tallahassee, FL.

Thompson, C. R., and Habeck, D. H. 1989. Host specificity and biology of the weevil *Neohydronomus pulchellus*, biological control agent of waterlettuce (*Pistia stratiotes*). *Entomophaga* 34(3):299-306.

US Army Engineer Waterways Experiment Station. 1981. The use of insects to manage alligatorweed. Instruction Report A-81-1. Vicksburg, MS.

Vogt, G. B. 1960. Exploration for natural enemies of alligator weed and related plants in South America. Special Report PI-4. Agr. Res. Serv., US Dept. of Agriculture, Washington, DC.

Release and Establishment of Insect Biocontrol Agents for Hydrilla Control

by
Ted D. Center,[1] F. Allen Dray, Jr.,[2] and W. C. Durden[1]

Introduction

The successful employment of nonnative insects for alligatorweed and waterhyacinth control in the United States during the 1960s and 1970s demonstrated the effectiveness of the introduction ("classical") approach toward biological control technology in aquatic ecosystems (Buckingham 1984). This success encouraged development of biological control programs to address other species of aquatic weeds. As a result, the US Department of Agriculture, in collaboration with the US Army Corps of Engineers, later established projects for biological control of several new target species. Biological control of *Hydrilla verticillata* (hydrilla) was identified as a top priority by both agencies.

Hydrilla verticillata L. is the most severe aquatic weed in the southern United States. During the period 1982 to 1989, it was estimated to infest 40,000 to 60,000 acres in Florida alone (Schardt and Schmitz 1989), and rapidly expanded into northern regions. Herbicidal control of hydrilla has proven expensive and temporary. Partial herbicidal treatment of an infestation at a single lake (Lake Istokpoga) during 1989 cost the State of Florida $1.2 million. This constituted 20 percent of the state's total aquatic weed control budget for that year. Clearly, widespread herbicidal control of hydrilla is beyond the means of most public agencies, and alternatives are desperately needed.

Worldwide faunal inventories initiated in 1981 resulted in the selection of several candidate hydrilla biological control agents from tropical and subtropical regions for introduction into US quarantine (Balciunas 1982, 1983, 1984, 1985; Balciunas and Dray 1985). The first insects selected were the tuber-feeding weevil *Bagous affinis* and the leaf-mining fly *Hydrellia pakistanae* from India. Host range tests confirmed that these two insects fed and thrived only on hydrilla (Buckingham 1988, 1989, 1990), and both were released at field sites in Florida during 1987 (Center 1989, 1990).

These worldwide surveys were followed by more detailed studies in Australia. Five candidate species were eventually evaluated (Balciunas 1987; Balciunas and Center 1988; Balciunas, Center, and Dray 1989). Two of these, the leaf-mining fly *Hydrellia balciunasi* and the stem-boring weevil *Bagous* n. sp., were imported to US quarantine for more testing (Balciunas 1987, Balciunas and Center 1988, Buckingham 1990). The former species was released in 1989, and the latter species has been approved for release.

Additionally, four stream-dwelling species of moths were found. These were of interest because of their perceived potential for hydrilla control in flowing systems. One species *(Strepsinoma repititalis)* was eliminated from further consideration because its diet was not restricted to hydrilla (Balciunas, Center, and Dray 1989). A second species *(Nymphula dicentra)* may be conspecific with *Parapoynx diminutalis*, an Asian species already present in the United States. Further research on *Aulacodes siennata* has been postponed due to the loss of field populations in Australia. A fourth species *(Nymphula*

[1] US Department of Agriculture, Agricultural Research Service, Aquatic Plant Management Laboratory, Fort Lauderdale, FL.
[2] University of Florida, IFAS Fort Lauderdale Research and Education Center, Fort Lauderdale, FL.

eromenalis) has not yet been fully studied to evaluate its potential.

Although much remains to be done in Australia, this facet of the project has been largely abandoned in order to focus resources on other aspects. Meanwhile, additional research has been initiated in China to study biological control agents that might be useful against hydrilla in temperate regions (Balciunas 1990). As a result, a Chinese *Hydrellia* has already been imported to US quarantine (see Balciunas 1991 and Buckingham 1991). Also, an African midge presumed to be the causal agent of severe tip damage and stunting of hydrilla plants in Lake Tanganyika was collected and imported to US quarantine (see Buckingham 1991). Further work with this insect seems warranted.

Objectives

Two approaches may be followed to implement biological control: the augmentation-manipulation approach or the introduction approach. The augmentation-manipulation approach is one in which the bioagent is applied to the weed in varying numbers at selected times. The use of herbivorous fish is an example of this. The introduction approach is one in which natural enemies are introduced or inoculated into a new area and allowed to increase to controlling levels on their own. This method is of greatest utility against naturalized exotic pests that have been introduced free of their natural enemies. This latter approach has been the focus of our biological control program.

Several critical research phases are cardinal to the introduction approach. The first phase involves faunal inventories of the target weed within its native range to assess the availability of potential bioagents for introduction into the United States. Associated with this is follow-up research at the foreign location to ascertain the potential safety and effectiveness of the prioritized candidates. Without this phase, the supply of new bioagents dwindles. This happened in the aquatic program after the overseas work on waterhyacinth terminated in the mid-1970s. New foreign exploration was not initiated until several years later. As a result, no new bioagents were released on aquatic weeds for a 10-year period between 1977 and 1987.

The foreign research program feeds directly into a domestic quarantine research phase, which is equally critical. The purpose of this phase is to further test the host specificity (i.e., safety) of candidate bioagents. This is done by exposing them, under quarantine conditions, to native plants or economic plant species that may be perceived to be at risk but which are unavailable at the foreign location. The agencies charged with certifying the safety of these organisms are unlikely to grant permission for their release without this information.

The quarantine research feeds directly into the release program, which is the third critical phase, and the focus of this report. This phase involves the deliberate reassociation of the foreign bioagent with domestic infestations of the target weed. Field colonies are established and, once developed, serve as a source of insects for later inoculation at other sites. Our objective for fiscal year 1990 was to establish field colonies of hydrilla bioagents and to begin to distribute them elsewhere.

Results and Discussion

Bagous affinis was first released in April 1987 at Lake Tohopekaliga in central Florida (Center 1989). More than 10,000 adults, plus an unknown number of eggs and infested tubers, had been released at 10 sites in Florida by mid-1989 (Center 1990). Due to an overcommitment of available resources, we were unable to conduct postrelease studies to confirm establishment at any of the release sites. Only one additional release was made during 1990 (Table 1) before we lost our laboratory colony. At that time we were hopelessly overburdened with other, more promising new bioagents, and were forced to terminate our involvement with this insect. We are still hopeful, however, that it will be used against

Table 1
Releases of Hydrilla Tuber Weevil (*Bagous affinis*) in Florida

Site	County	Release Dates	No. Releases	Number Released[1]				Infested Tubers[2]	Status[3]
				Eggs	Larvae	Pupae	Adults		
Lake Tohopekaliga	Osceola	4/87-5/87	2	0	0	0	1,487	No	I
Sunshine Parkway east	Palm Beach	6/87	1	0	0	0	250	No	I
Sunshine Parkway west	Palm Beach	10/87	1	0	0	0	203	No	I
St. John's River @ SR46	Seminole	6/88-7/88	8	0	0	0	2,043	No	I
St. John's River @ Hatbill Park	Brevard	7/87-6/88	1	U	0	0	360	Yes	I
Harney Pond Canal	Glades	9/87-9/89	2	0	0	0	226	No	I
Everglades Holiday Park	Broward	9/87	1	0	0	0	100	No	I
Lake Osborne	Palm Beach	11/87	1	0	0	0	200	No	I
Billy Peeples' Farm	Glades	10/88-3/89	10	U	0	0	4,225	No	N
Rodman Reservoir[4]	Putnam	1/89-3/89	3	U	0	0	1,601	Yes	P
Naples Manor	Collier	5/90	1	0	71	131	783	No	I
Total			31	U	71	131	11,478		

[1] Designation of U indicates members of the stage in question were known to be in the material released, but actual counts were unavailable.
[2] Affirmative responses in this column indicate that tubers were released from our cultures without being examined for *B. affinis*.
[3] Designation P represents a weak positive indication, N represents no positive indication, and I indicates we were unable to evaluate for establishment.
[4] A *Bagous affinis* population persisted briefly at this site during a reservoir drawdown, but rising water levels likely eliminated it.

hydrilla in California. Dr. Buckingham is attempting to secure additional insects from India and to develop new colonies for this purpose.

Hydrellia pakistanae was first released at Lake Patrick in Polk County, Florida, during October 1987. Numerous additional releases that brought totals to about 44,000 eggs, 4,600 larvae, and 600 adults were made during 1989 (Center 1990). Despite initial recoveries of small numbers of flies at two sites (Center 1989), we were unable to conclude that populations had established at any of the release sites by the end of 1989.

We felt that we were releasing too few flies at too many sites that were much too large. Alternatively, we decided to repeatedly release large numbers of flies within enclosures at a single small site until either a population had become established or we were convinced that they could not be established at that site.

Also, whereas we had been releasing eggs as soon as they could be collected from oviposition chambers and counted, we elected instead to hold them a bit longer prior to their release. Thereafter, we placed the eggs on hydrilla into water-filled pans and held them in the laboratory for 10 to 14 days before moving them to the field. This resulted in a change in strategy, from the release of eggs to the release of a range of stages (from eggs to relatively large larvae) (see Figure 1).

For the establishment of initial field colonies, we selected two small ponds. One was a drainage pond for a newly constructed Interstate highway (the Hacienda Village site), and the other was a borrow pit located at the West Palm Beach International Airport.

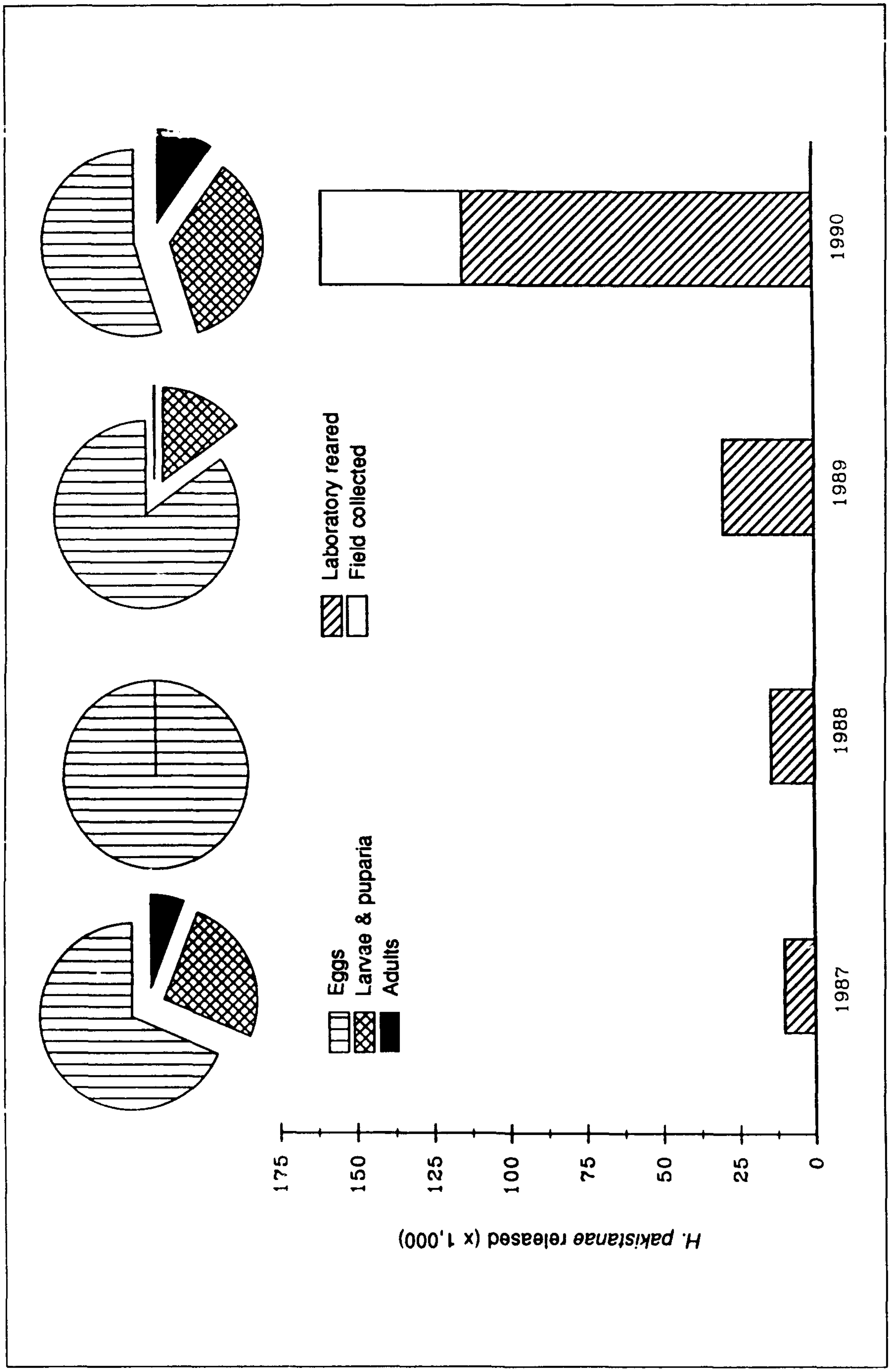


Figure 1. Summary of data on the increase in numbers of Hydrellia pakistanae released from 1987 to 1990, the change in proportions of developmental stages released (pie charts), and the increasing importance of field colonies as a source of insects

We placed a shallow cage on the surface of the "topped-out" hydrilla mat and anchored the cage to the bottom at each site. The cage was constructed from 2-in.-square channeled aluminum framing (the type used to construct screened patios). It consisted of an open frame (1 by 1 m) on the bottom with a hinged, screened lid on top. D-rings were secured to the sides of the frame, and PVC-pipe poles of appropriate length were passed through the D-rings and pounded into the bottom to hold the cage in place. The aluminum framing was filled with polystyrene to provide flotation.

Releases were usually made by opening the hinged top and placing hydrilla that was infested by immature stages of the flies into the existing mat. We continued releasing in this manner until it appeared that the flies had established at that locus. We then moved the cage to another spot within the same area and repeated the process. We released as many insects as we could possibly procure, as often as possible (frequently at weekly intervals).

Nine releases were made at the highway site during January and February 1990, which consisted of nearly 29,000 eggs and larvae. Seven releases were made at the airport site between November 1989 and January 1990, including 16,000 eggs, larvae, and puparia. Populations quickly established at both sites.

Encouraged by the results at the small sites, we then attempted to establish the flies at a larger site. We chose Lake Hicpochee for this purpose. Lake Hicpochee is located at the southwest end of Lake Okeechobee. The lake is bisected by the Caloosahatchee River. We chose the section on the north side of the river as a release area and began making releases in March 1990. This continued until September 1990, during which time 25 releases were made that totaled over 30,000 insects (Table 2). (We also made three releases during 1989 comprising a total of about 5,000 insects, but these failed to establish.)

Unfortunately, when the site was revisited on 7 September 1990, the hydrilla was gone. Almost all of the aquatic vegetation appeared to have been scoured by a massive movement of water through the site. A few small patches of hydrilla were found, however, and a few adult *H. pakistanae* were collected from them. Thus, we felt that a population of *H. pakistanae* probably was established in the area.

The experience at Lake Hicpochee disclosed a disadvantage to using an open system for the purpose that we had in mind, namely establishing field colonies. Although infested plants may have persisted somewhere in the system, we had no way of ascertaining their location. We decided that at least during the early stages of the release process, it was better to use small, closed systems where the hydrilla population was confined to a limited area.

We now have *H. pakistanae* populations established at the airport site, the Hacienda Village site, and the Orangebrook Country Club Pond in Hollywood. We had intended to establish only *H. balciunasi* at the latter site, but contamination of our colonies resulted in the accidental release of unknown numbers of *H. pakistanae* there. It now harbors a well-established population of *H. pakistanae*.

A population has also established at a small lake located about 2 miles from the Hacienda Village site. Flies were not intentionally released in this location, but have apparently gotten there on their own. We have also made initial recoveries of flies from Lake Seminole, from the Wacissa River, at Eagle Bay on Lake Okeechobee, and at two Lakeview sites. Although the status of fly populations at these latter sites is uncertain, initial indications are promising.

The key factor in finally achieving establishment of *H. pakistanae* seems to have been our ability to acquire sufficient numbers of insects and to concentrate them within a small area. As can be seen in Figure 1, the number of insects that we produced increased dramatically during 1990. This was largely due to supplemental funding provided by a state agency (Florida Department of Natural

Table 2
Releases of Hydrilla Leaf-mining Fly (*Hydrellia pakistanae*) in Florida and Southern Georgia

Site	County	Release Dates	No. Releases	Number Released[1]				Infested Sprigs[2]	Status[3]
				Eggs	Larvae	Puparia	Adults		
Lake Lenore	Polk	10/87	1	6,000	2,600	0	600	No	N
Rodman Reservoir @ Spike Club	Marion	11/87	1	1,000	0	0	0	No	N
Everglades Holiday Park	Broward	2/88-6/88	2	6,177	0	0	0	No	P
Lake Hicpochee[4]	Glades	3/88-9/90	28	5,093	31,869	578	0	No	P
Lake Osborne	Palm Beach	5/88	1	3,870	0	0	0	No	I
Fisheating Bay, L. Okeechobee	Glades	8/88-3/89	2	387	3,078	0	0	Yes	N
Big Bear Beach, L. Okeechobee	Glades	11/88-II/90	6	9,749	215	0	1,034	No	I
Eagle Bay Island, L. Okeechobee	Okeechobee	11/90-12/90	5	34,551	U	U	3,000	Yes	P
North New River Canal	Broward	1/89	1	0	0	0	0	Yes	I
Lake Tohopekaliga	Osceola	3/89-12/90	3	3,227	143	0	3,300	No	I
Sears Lake	Polk	3/89	2	3,531	0	0	0	No	I
US27/SR78 canal	Glades	4/89	1	410	119	0	0	No	I
Palm Beach Airport	Palm Beach	11/89-1/90	7	13,223	3,140	157	0	No	E
Lake Seminole, Georgia	Decatur	6/90-10/90	5	20,110	8,024	747	3,244	No	I
Hacienda Village	Broward	1/90-2/90	9	18,582	10,249	0	0	No	E
Wacissa Springs @ Horsehead Run	Jefferson	10/90	1	10,430	1,561	153	3,500	No	I
Wacissa Springs @ boat ramp	Jefferson	11/90	1	0	600	600	0	Yes	I
Wacissa Springs 1 mi. south of springs	Jefferson	10/90	1	0	0	588	0	Yes	P
Little River	Jefferson	10/90	1	0	500	500	334	Yes	I
Lakeview north	Broward	11/90	2	0	650	650	0	Yes	I
Lakeview south	Broward	11/90	1	0	100	100	0	Yes	E
Lake Robin Hood	Lake	12/90	1	0	0	0	1,200	No	I
Orangebrook Golf Club[5]	Broward	2/90-7/90	10	U	U	U	U	Yes	E
Total			92	136,340	62,848	4,073	16,212		

[1] Designation of U indicates members of the stage in question were known to be in the material released, but actual counts were unavailable.
[2] Affirmative responses in this column indicate that tubers were released from our cultures without being examined for *Hydrellia pakistanae*.
[3] Designation N represents no positive indication, P represents a weak positive indication, I indicates we were unable to evaluate for establishment, and E represents a strong positive indication of establishment.
[4] A *Hydrellia pakistanae* population persisted briefly at this site during a reservoir drawdown, but rising water levels eliminated this population.
[5] This was originally a *H. balciunasi* release site. By 9 February 1990, however, our *H. balciunasi* cultures had become contaminated with *H. pakistanae*. Thus, subsequent releases at this site contained an unknown number of *H. pakistanae*.

Resources), but it is also a result of improvements in our rearing procedures. We have now begun to recollect from field colonies as a means of supplying insects for release at other sites. We expect field populations to become our principal source of *H. pakistanae* within the next 1 or 2 years.

Hydrellia balciunas was first released in a small pond at the Orangebrook Country Club in Broward County, Florida, on 1 September 1989 (Center 1990), employing the strategy described above. By April 1990 we had released about 12,000 eggs and larvae by making 27 separate releases into small enclosures at weekly intervals (Table 3).

A single adult *H. balciunasi* was recovered about 25 m from the enclosure, so we felt that it was established at the site. However, later collections of hundreds of adults provided only *H. pakistanae*, which to our knowledge had never been released there. Further checking revealed that our *H. balciunasi* colonies were contaminated and overwhelmed by *H. pakistanae*, and that this had been true for some time. We later learned that the original colonies at the Gainesville quarantine laboratory (which provided our original stock) were also contaminated. We therefore purged our colonies by releasing the remaining material at the site.

We received "clean" stock from Gainesville at a later data and are now in the process of producing new pure colonies of this species. However, the Orangebrook pond could no longer be considered a *H. balciunasi* site, although it may persist there in very low numbers.

Future Studies

We plan to continue our attempts to establish *H. pakistanae* at large field sites. We will most likely focus on Lake Okeechobee, and possibly Lake Seminole. We will also renew attempts to establish field colonies of *H. balciunasi*, first at small sites and later at larger sites. As field populations become available, we will begin to evaluate their impacts.

We will collect from field sites and inoculate experimental sites with sufficient numbers to ensure rapid establishment, and then compare the hydrilla populations at these sites to hydrilla at noninoculated sites. This will enable us to determine which aspects of the hydrilla populations are altered by these insects. We will then use this information to study the long-term impacts of the bioagents upon the plant populations by monitoring characteristics that seem most important.

In addition, we will begin to develop laboratory colonies of and begin a release program with the newest hydrilla bioagent, *Bagous* n. sp. This Australian weevil has been approved for release, and we are awaiting permits. We will eventually work toward evaluation of this insect, as well.

Table 3
Releases of Hydrilla Leaf-mining Fly (*Hydrellia pakistanae*) in Florida

Site	County	Release Dates	No. Releases	Number Released[1] Eggs	Larvae	Puparia	Adults	Infested Sprigs[2]	Status
Orangebrook Golf Club	Broward	2/89-4/90	27	1,127	10,936	85	U	Yes	P[3]

[1] Designation of U indicates members of the stage in question were known to be in the material released, but actual counts were unavailable.
[2] Affirmative response in this column indicates that tubers were released from our cultures without being examined for *H. balciunasi*.
[3] Designation P represents a weak positive indication. By 9 February 1990, our *H. balciunasi* cultures had become contaminated with *H. pakistanae*. Thus, subsequent releases at this site contained unknown numbers of *H. balciunasi* and *H. pakistanae*.

References

Balciunas, J. K. 1982. Overseas searches for insects for control of aquatic plants. Pages 141-154 in *Proceedings, 16th Annual Aquatic Plant Control Research Program and Operations Review*. Miscellaneous Paper A-82-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1983. Overseas searches for insects on hydrilla in Southeast Asia and Australia. Pages 104-114 in *Proceedings, 17th Annual Aquatic Plant Control Research Program and Operations Review*. Miscellaneous Paper A-83-9. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1984. Overseas surveys of biocontrol agents for hydrilla. Pages 76-84 in *Proceedings, 18th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-84-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1985. Final report on the overseas surveys (1981-1983) for insects to control hydrilla. Technical Report A-85-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1987. Australian insects to control hydrilla. Pages 57-66 in *Proceedings, 21st Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-87-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1990. Biocontrol agents from temperate areas of Asia. Pages 25-33 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K. 1991. See pp 166-171 in this proceedings.

Balciunas, J. K., and Center, T. D. 1988. Australian insects to control hydrilla, an update. Pages 312-319 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K., and Dray, F. A. 1985. The search for insects to control U.S. hydrilla populations. Pages 75-78 in *Proceedings, 19th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-85-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balciunas, J. K., Center, T. D., and Dray, F. A., Jr. 1989. Testing suitability of Australian bioagents for control of *Hydrilla verticillata*. Pages 24-27 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Buckingham, G. R. 1984. Biological control of weeds by insects. *J. Georgia Entomol. Soc.* 19(3):62-78.

Buckingham, G. R. 1988. Quarantine research program—Hydrilla insects. Pages 307-311 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Buckingham, G. R. 1989. Quarantine work—Insect biocontrol for hydrilla. Pages 28-33 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Buckingham, G. R. 1990. Quarantine laboratory: Research for hydrilla control. Pages 34-38 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-90-3.

US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Buckingham, G. R. 1991. See pp 172-175 in this proceedings.

Center, T. D. 1989. Release and establishment of insect biocontrol on hydrilla. Pages 34-40 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Center, T. D. 1990. Release, establishment, and evaluation of insect biocontrol agents for aquatic plant control. Pages 39-49 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schardt, J. D., and Schmitz, D. C. 1989. 1989 Florida aquatic plant survey. Technical Report 90-CGA. Florida Dept. Natural Resources, Tallahassee, FL.

Biological Control of Eurasian Watermilfoil Using Plant Pathogens

by
Craig S. Smith[1] *and Linda E. Winfield*[1]

Introduction

The pathogenic fungus *Mycoleptodiscus terrestris* (MT) has demonstrated considerable potential for use as a mycoherbicide for the control of Eurasian watermilfoil, *Myriophyllum spicatum* L. (Gunner et al. 1990, Stack 1990, Winfield 1990). The focus of current research efforts is the development of formulations capable of controlling the plant in the field and techniques for their successful application.

This paper reports the results of two studies: (1) a greenhouse study to determine the relative susceptibility to MT of plants before and after canopy formation and (2) a field trial of a commercial MT formulation conducted in 0.4-acre ponds at the Lewisville Aquatic Ecosystem Research Facility.

Methods

Greenhouse timing study

The relative effectiveness of MT against Eurasian watermilfoil plants before and after canopy formation was evaluated by inoculating plants at different stages of growth. Plant cultures were started on two dates, 5 weeks apart, and were inoculated when the older plants had formed a canopy but the younger plants had not yet reached the surface.

For this experiment, rooted plants were cultured in acrylic cylinders 16.5 cm in diameter by 1.5 m in height, as described by Smart and Barko (1985). Cylinders were placed in a greenhouse under natural light and immersed to approximately half their height in temperature-controlled water tanks maintained at 20° ± 1° C (Figure 1).

Figure 1. Setup for greenhouse study of MT timing

The sediment in which plants were rooted was collected from Brown's Lake, Mississippi, using a Ponar dredge. Columns were filled with plant culture solution (Smart and Barko 1985) (see Table 1) and were aerated during the experiment by bubbling compressed air through them. The temperature and pH of the solution in each column were monitored approximately once a week during the experiment.

Table 1
Recovery of MT from Inoculated Culture Cylinders in the Greenhouse Timing-of-Application Study

Plant Segment	Number of Inoculated Cylinders from Which MT Was Recovered (percent)
Apical	0 (0%)
Middle	7 (58%)
Bottom	10 (83%)

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The first planting consisted of 18 cylinders, each planted with three 15-cm sprigs of Eurasian watermilfoil. Six cylinders were placed into each of three temperature-controlled tanks. Five weeks after planting the first cylinders, a second set of 18 cylinders was planted in the same fashion. Six cylinders were placed into each of the three tanks that already contained cylinders from the first planting. Six weeks after planting the second set of cylinders, four randomly selected cylinders from each tank (two from each planting) were removed, and the plant biomass and MT population size in these cylinders were determined (see below). Half of the remaining cylinders in each tank (i.e., two from each planting) were then inoculated with MT by adding 16.0 g of commercial MT formulation (Ecoscience Laboratories, Amherst, MA) to each column.

At harvest time, plants were removed from the cylinders and washed thoroughly with running tap water. Three 2.5-cm stem segments with attached leaves (one from the apex, one from the middle, and one from just above the root crown) were removed from each of the three plants from each column and plated to determine whether MT was present (see below). The remaining plant material was separated into roots and shoots, dried for 4 to 5 days at 100° C, and then weighed.

Stem segments to be assayed for MT were surface sterilized in 70 percent ethanol for 15 sec, blotted dry on sterile paper laboratory wipers, and rinsed twice with sterile distilled water. Then, leaf and stem pieces were plated separately on Martin's agar (Martin 1950). Approximately 3 days after plating, the presence or absence of MT-like fungi growing from the pieces of each plant segment was recorded. Fungal colonies appearing to be MT were plated on potato dextrose salts agar (Sneh and Stack 1990). Only colonies having the characteristic growth and appearance of MT on both media were recorded as MT.

Plant biomass data were analyzed as a randomized complete block experiment using two-way ANOVA. Plant age (precanopy or postcanopy formation) and time/treatment (initial, final/inoculated, final/control) were the two experimental factors. Cylinders from each of the three temperature-controlled tanks were considered a block in the analysis. Orthogonal contrasts were used to evaluate the effect of inoculation with the fungus on biomass, and the relative response of plants of different ages to inoculation. Treatment means were compared using Duncan's Multiple Range Test.

Pond experiment

A field test of the effectiveness of MT was conducted in ponds 40 and 41 of the Lewisville Aquatic Ecosystem Research Facility. Prior to planting, the ponds were rototilled, fertilized with ammonium sulfate at a rate of 500 lb/acre (560 kg/ha), and rototilled again to incorporate the fertilizer into the bottom sediments. The ponds were planted on 3 and 4 May 1990 with Eurasian watermilfoil collected from a nearby culture pond.

Milfoil stems were planted along the waterline as the ponds filled by inserting the lower end of the stems at least 10 cm into the bottom sediments and pressing sediments down around them. The deepest parts of the ponds were planted with groups of three plants spaced 0.5 m apart, while the remainder of the pond bottoms were planted with groups of two stems spaced 0.6 m apart. The sides of the ponds and areas shallower than 0.5 m were not planted.

Approximately 6 weeks after planting, each pond was divided lengthwise using curtains of Permalon pond liner material. On 15 June 1990, one side of each pond was inoculated with MT. Pellets of formulated MT were broadcast by hand using a plastic scoop at an approximate rate of 31 lb (dry weight) per acre (1.5 lb a.i./acre).

Biomass of milfoil in the half-ponds was measured just prior to inoculation and 4 weeks postinoculation by harvesting 1.0-m^2 quadrats. Four sampling stations were arranged at 10-m intervals along the long axis of each

half-pond, starting from the valve end. For the initial sample, one quadrat was harvested at each sampling station. For the 4-week sample, two quadrats were harvested 1.0 m from the sampling station along randomly chosen diagonals. All Eurasian watermilfoil plants rooted in each sample quadrat were excavated from the sediments by hand, washed in situ, dried at 100° C to a constant weight, and weighed.

The abundance of MT on milfoil plants and in the water was measured by plating on Martin's agar. A water sample and a plant sample for this purpose were collected from each sampling station weekly, beginning just prior to inoculation. Water samples were subsurface grab samples collected directly in sterile Whirl-Pak bags. One-milliliter aliquots of water samples were spread on Martin's agar, and colonies having the characteristic morphology of MT were counted approximately 3 days after plating. Plant samples were entire plant stems, collected by hand. Segments from the apex, middle, and bottom of each stem were assayed for MT as described above. As before, suspected MT colonies were plated onto potato dextrose salts agar, and only those which retained the appearance of MT on that medium were considered to be MT.

The temperature of the water in the ponds was measured just below the surface (10-cm depth), at approximately the depth where Eurasian watermilfoil forms a canopy. Initial measurements were made with a thermometer; on day 7 after inoculation, a datalogger was set up to monitor water temperatures hourly until the end of the experiment.

Comparisons of final (4-week) measurements of plant biomass in the treated and untreated pond halves were made using a paired t-test. Each pair consisted of the biomass values for quadrats in the same position in the pond halves, but on opposite sides of the divider. Differences between paired samples were tested against the null hypothesis that they were equal to the average difference between the plant biomass on treated and control sides of the pond at the time of inoculation.

Results

Greenhouse timing study

Four weeks after inoculation, the biomass of plants treated with MT had not increased from that prior to inoculation, while the biomass of untreated controls had more than doubled (Figure 2). Final biomass and the response to inoculation with MT were essentially the same for plants in both the precanopy and postcanopy formation groups.

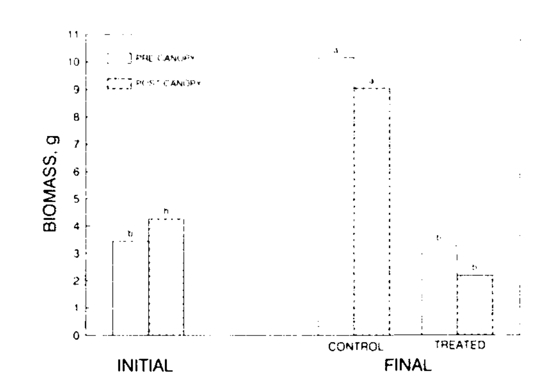


Figure 2. Initial (preinoculation) and final (4 weeks postinoculation) biomass of plants treated with MT or uninoculated (control). Plants were either inoculated before (precanopy) or after (postcanopy) they had formed a canopy at the surface. Bars with the same letter did not differ significantly at P = 0.05

Although MT was not detected in any of the initial or control plants, it was frequently detected in middle and stem base pieces of plants from the inoculated columns (Table 1). Even in the inoculated columns, MT was never isolated from apical plant pieces.

Although the columns were partially immersed in water tanks maintained at 20° C, temperatures in the columns were typically near 25° C and varied by several degrees among columns and dates (data not shown).

Pond experiment

By the time of inoculation, watermilfoil in the ponds had reached an average biomass of

27.7 g (dry mass) m^{-2}. *Myriophyllum spicatum* biomass in the left (treated) half of pond 40 was considerably higher than that in the other three ponds (Figure 3). Four weeks after inoculation, plant biomass in all pond halves had declined slightly. A paired t-test revealed that differences between the plant mass in treated and controlled pond halves were not significantly different ($P > 0.05$) from those existing prior to inoculation. MT was never detected in any of the water or plant samples from the ponds.

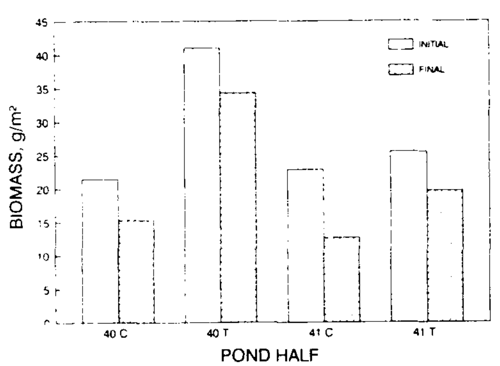


Figure 3. Biomass of Eurasian watermilfoil plants in treated (T) and control (C) halves of Lewisville ponds 40 and 41, just prior to inoculation with MT (initial) and 4 weeks after inoculation (final)

Temperatures in the two ponds ranged from 33° to 35° C at the surface to 31° to 32° C near the bottom immediately after inoculation. During the 4 weeks following inoculation, maximum daytime subsurface temperatures were typically 33° to 37° C, decreasing to 28° to 30° C by the end of the night.

Discussion

In greenhouse cylinders, inoculation with MT resulted in a substantially lower biomass of Eurasian watermilfoil than was produced by uninoculated controls. Plant age had no discernible effect; MT was equally effective against plants before and after canopy formation. MT was readily reisolated from lower and middle stem pieces from inoculated plants, showing that the fungus had become well established in parts of the plant that had likely been present at inoculation. However, the failure to detect MT in apical stem pieces raises doubt that secondary MT infections were keeping pace with new plant growth, even on the severely impacted plants in these treatments. If this is true in other circumstances, biological control of Eurasian watermilfoil by MT will be limited to that produced by the initial inoculum and any propagules produced by it.

Elevated water temperatures in the Lewisville ponds probably contributed to the failure of MT to control Eurasian watermilfoil. The temperature limits for MT effectiveness have not been determined, but MT grows rather poorly on standard microbiological media at 30° C and above (J. Stack, personal communication). Effective use of MT in shallow ponds in the southern United States will probably require inoculation in the early spring. At the Lewisville facility, inoculation with MT in late April would probably be optimal. By then, watermilfoil plants will have formed a canopy at the water surface, and the water temperature should be approximately 25° C.

An obvious shortcoming of the pelletized formulation of MT is its limited ability to stick to plants. In greenhouse experiments, efficient retention of pellets by the tightly packed plant canopy undoubtedly contributes to the observed effectiveness of MT. In the ponds, few of the MT pellets were intercepted by the plant canopy, and most settled to the surface of the sediments. Even if infection of plants by spores produced on the surface of pellets is a major means of disease transmission, pellets on the sediment surface are not likely to contribute to the infection of plants. Development of an improved formulation that is more effectively intercepted by the plant canopy should precede any additional field trials of MT.

References

Gunner, H. B., Limpa-amara, Y., Bouchard, B. S., Weilerstein, P. J., and Taylor, M. E. 1990. Microbiological Control of Eurasian Watermilfoil; Final Report. Technical Report-A-90-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Martin, J. P. 1950. Use of acid rose bengal and streptomycin in the plate method for estimating soil fungi. *Soil Sci.* 69:215-232.

Smart, R. M., and Barko, J. W. 1985. Laboratory culture of submersed freshwater macrophytes on natural sediments. *Aquat. Bot.* 21:251-263.

Sneh, B., and Stack, J. 1990. Selective medium for isolation of *Mycoleptodiscus terrestris* from soil sediments of aquatic environments. *Appl. Environ. Microbiol.* 56:3273-3277.

Stack, J. P. 1990. Development of the fungal agent *Mycoleptodiscus terrestris* for the biological control of Eurasian watermilfoil (*Myriophyllum spicatum* L.). Pages 85-90 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Winfield, L. E. 1990. Biological Control of Eurasian Watermilfoil. Pages 79-84 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Biotechnical Approaches to Aquatic Plant Management: Genetic Engineering

by
S. L. Kees[1] *and E. A. Theriot*[1]

Introduction

This work unit addresses the use of genetically engineered microorganisms for aquatic plant biocontrol. In June 1987, a workshop was conducted at the Waterways Experiment Station to determine the feasibility of applying genetic engineering technology to a biomanagement strategy for submersed aquatic plants (Theriot 1987). That committee of technical experts advised that availability of host-specific microbes was essential for the application of genetic engineering technology to a microbial biocontrol strategy. Based on that guidance, our purpose has been to identify mechanisms of specificity at both the organismic and molecular levels.

The search for mechanisms of specificity at the organismic level was conducted by Dr. Craig Smith and the University of Wisconsin at Madison (Smith et al. 1989). The WES research focused on mechanisms of specificity at the molecular level.

Our pursuit of mechanisms of specificity at the organismic or cellular level led to the understanding that there are four distinct stages at which specific association may occur between microbe and host plant (Theriot and Kees 1989). The assay developed by the University of Wisconsin was designed to evaluate association at each of these levels. The labor-intensive and time-consuming nature of this assay necessitated the development of a faster, simpler assay that would allow screening of large numbers of microbes from a perspective of visibly quantifiable pathogenesis. The rapid screening assay protocol is described in the Materials and Methods section which follows.

Plant lectin involvement in the association of host-specific microbes has been documented in terrestrial systems (Dazzo and Hubbell 1975). Our objectives were to determine whether lectins exist in hydrilla *(Hydrilla verticillata)* and/or Eurasian watermilfoil *(Myriophyllum spicatum)*, to identify the haptenic specificity of the lectin for both target species, and to demonstrate lectin-mediated specific agglutination of fungal hyphae. Lectin has been isolated from both plant species and has, in each case, demonstrated an affinity for the six carbon sugar α-L-fucose. Hydrilla lectin appears to be the same in tubers as it is in stems and leaves; milfoil lectin appears to be the same in seedpods as it is in stems and leaves. No detectable quantities of lectin were found in the roots of either plant species.

Having verified the presence of lectin for both plant species and lectin haptenic specificity, our next objective was to evaluate the importance of the molecular interaction between plant surface lectins and microbial surface antigens as a mechanism of specific association.

Materials and Methods

Rapid screening bioassay

Cryosamples of approximately 400 fungal isolates were plated for purity on potato dextrose agar (PDA), and then transferred to PDA slants and refrigerated until tested in the rapid screening bioassay. Four agar plugs were taken from 7-day-old PDA cultures of the test isolate (using a sterile no. 3 cork borer) and were placed facedown on a 4.0-cm

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

apical segment of healthy leafy plant tissue in glass petri dishes (100 by 20 mm) containing 40 ml of sterile Smart and Barko medium (Smart and Barko 1985).

The assay was run for 7 days on a 16:8-hr light cycle at room temperature. Both treated and untreated controls were run simultaneously with each group of test isolates. The treated control for hydrilla isolates was *Macrophomena phaseolina*; the treated control for milfoil isolates was *Mycoleptodiscus terrestris*.

Pathogen selection

Four known pathogens were selected for evaluation of the lectin association mechanism. The two hydrilla pathogens tested were *Macrophomena phaseolina* and *Fusarium roseum culmorum*. The two milfoil pathogens tested were *Mycoleptodiscus terrestris* and *Colletotrichum gloeosporioides*.

Pathogen bioassay

Pathogens were grown on petri plates of Richard's V-8 agar containing 250 mg/L of chloramphenicol for 4 days. Six agar plugs from a sterile no. 3 cork borer were used to inoculate 125 ml of Richard's V-8 broth containing 250 mg/L of chloramphenicol. The liquid cultures were grown on a rotary shaker at 160 rpm for 3 to 4 days at room temperature. Fungal cultures were homogenized for 2 min in a Sorvall Omni-Mixer (speed setting, 10) submersed in an ice bath to dissipate heat.

Five milliliters of the homogenized fungal mycelium was added to 45 ml of sterile Smart and Barko medium (Smart and Barko 1985) containing a 10.0-cm apical segment of healthy, leafy plant tissue. Symptoms of gross pathogenesis were recorded at 1, 3, 7, and 14 days postinoculation.

Fungal attachment assay

Fungal pathogens were grown per the pathogen bioassay protocol described above.

One-centimeter-long leaf and stem segments of plant tissue were surface sterilized in a 10-percent solution of hydrogen peroxide for 1 min, then rinsed three times in sterile distilled water and once in sterile buffered Tween 80 for 30 min to allow dissipation of residual hydrogen peroxide. Six plant fragments were placed in sterile Smart and Barko medium and treated with a mycelial suspension of each of the four fungal pathogens for 0 and 16 hr. At 0 and 16 hr, respectively, three plant fragments were removed from the fungal suspension, rinsed three times in sterile distilled water to remove unattached cells, and then sonicated for 3 min with an Artek sonic dismembrator model 150 (setting, 48) in 7.5 ml of sterile distilled water to remove tightly bound microbes. Fungal attachment was determined by dilution plating the sonication medium on PDA containing chloramphenicol. The attachment index represents the number of colony forming units per milliliter of sonication medium.

Agglutination of fungal hyphae

Fungal pathogens were grown per the pathogen bioassay protocol described above except that fungal mycelia were filtered through five layers of sterile cheesecloth prior to homogenization. The mycelia were then rinsed three times in sterile distilled water and adjusted to a 2-percent suspension in sterile phosphate buffered saline.

Sterile glass depression slides containing 50 µL of the 2-percent suspension of fungal hyphae and 50 µL of affinity chromatography-purified lectin at physiological concentrations were incubated for 1 hr at room temperature. The slides were then examined for evidence of agglutination with a Leitz Diaplan standard light microscope equipped with phase-contrast optics at 40× and 100× magnification. Untreated controls were run simultaneously and were treated with 50 µL sterile phosphate buffered saline in lieu of plant lectin. Hyphal agglutination was determined based on comparison with untreated controls.

Results

The rapid screening bioassay resulted in the identification of ten new potential pathogens on hydrilla and nine new potential pathogens on Eurasian watermilfoil (Table 1).

The pathogen bioassay against hydrilla (Figure 1) showed minor pathogenesis at day 3 for both *M. phaseolina* and *M. terrestris*. By day 7, all four pathogens significantly impacted the growth of hydrilla. *Macrophomena* was by far the most pathogenic.

Table 1
Isolates Identified in Rapid Screening Bioassay

H. verticillata Pathogens	
FHy 20	8F 7
FHy 26	8F 8
FQ 9	9F 8
FR 7	10F 11
4F 3	12F 1
***M. spicatum* Pathogens**	
FH 12	LMy 1
FH 14	LMy 2
FE 1	LMy 9
FM 1	LMy 10
FMy 3	

The second assay addressed microbial attachment (Figure 2). According to the literature, any specific attachment that is going to occur does so within the first 6 to 12 hr. At 16 hr postincubation, none of the pathogens demonstrated significant attachment to hydrilla except *Colletotrichum*, which has been reported extensively in the literature to exhibit considerable nonspecific attachment to a number of surfaces, including acid-washed glass slides.

The third assay evaluated the agglutination of fungal hyphae by affinity chromatography-purified lectin at physiological concentrations (Table 2). None of the pathogens tested were agglutinated, i.e. recognized, by hydrilla lectin. This is, of course, consistent with hydrilla attachment assay data, which suggest the absence of specific attachment. Agglutination of fungal hyphae by milfoil lectin occurred for all pathogens tested except *M. phaseolina*.

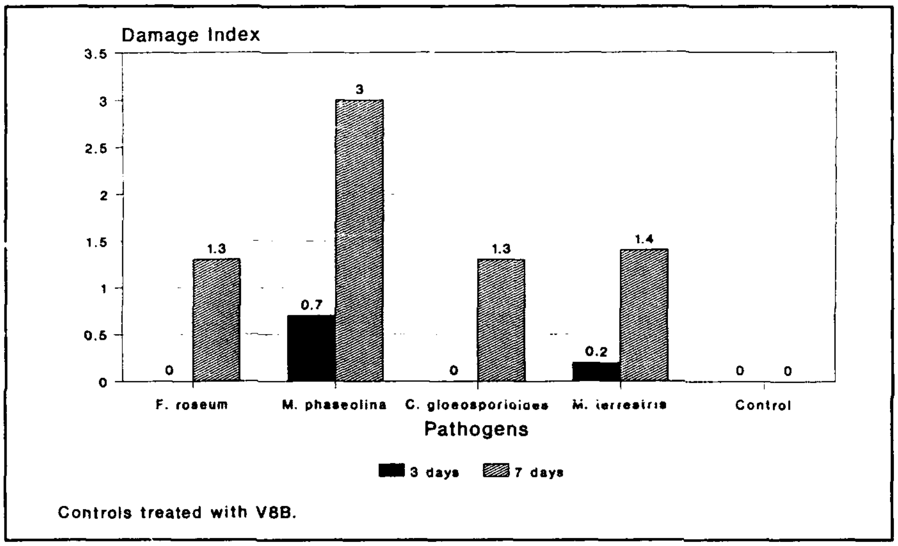


Figure 1. Impact of selected pathogens on hydrilla at days 3 and 7

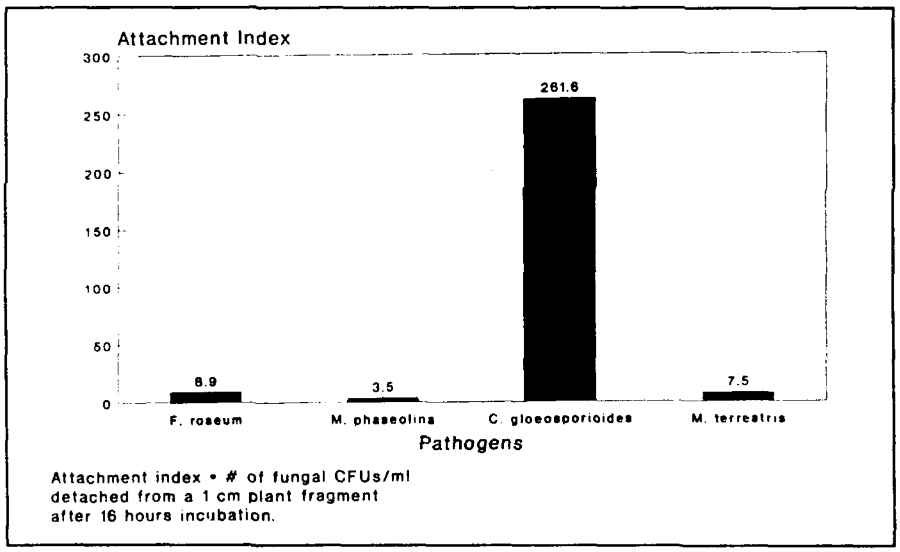


Figure 2. Attachment of selected pathogens to intact hydrilla tissues within the first 16 hr

Table 2 Agglutination of Fungal Hyphae by Plant Lectins[1]		
Pathogens	**Hydrilla Lectin**	**Eurasian Lectin**
F. roseum	-	+
M. phaseolina	-	-
C. gloeosporiodes	-	+
M. terrestris		+

[1] Symbols denote occurrence (+) or absence (-) of agglutination.

Evaluation of the lectin-mediated association mechanism has produced data that are consistent with and lend credence to the speculation that lectins may have some function in inhibiting fungal growth and/or spore germination (Barkai-Golan, Mirelman, and Sharon 1978; Mirelman et al. 1975). In the case of hydrilla, when there was no specific attachment to plant tissue in the first 16 hr, there was no agglutination of fungal hyphae by affinity chromatography-purified lectin, and measurable pathogenesis ensued.

The attachment data for milfoil (Figure 3) show a high degree of specific attachment for *Fusarium* and, to a lesser degree, *Colletotrichum*. Again, bearing in mind the propensity of *Colletotrichum* toward nonspecific binding, it would appear that *Fusarium* is the only pathogen demonstrating specific attachment.

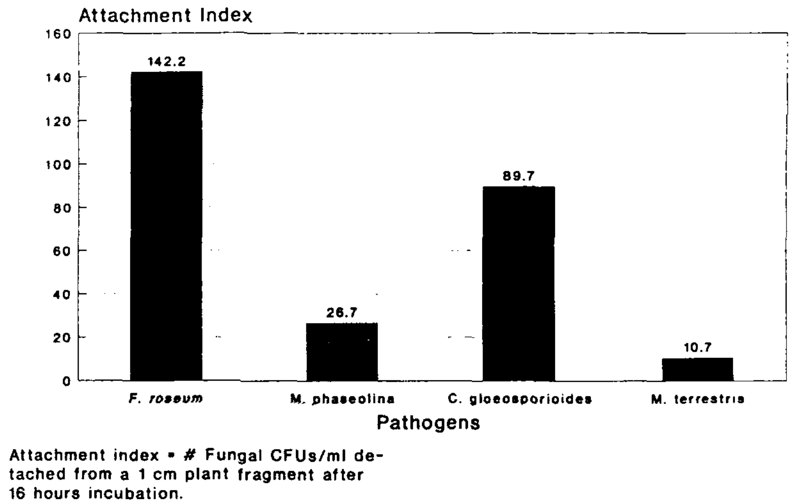


Figure 3. Attachment of selected pathogens to intact milfoil tissues within the first 16 hr

The pathogen bioassay data for milfoil (Figure 4) show all pathogens except *Fusarium* having at least minor impact on the species by day 3. This trend persisted through day 7, with *Macrophomena* again being the most pathogenic.

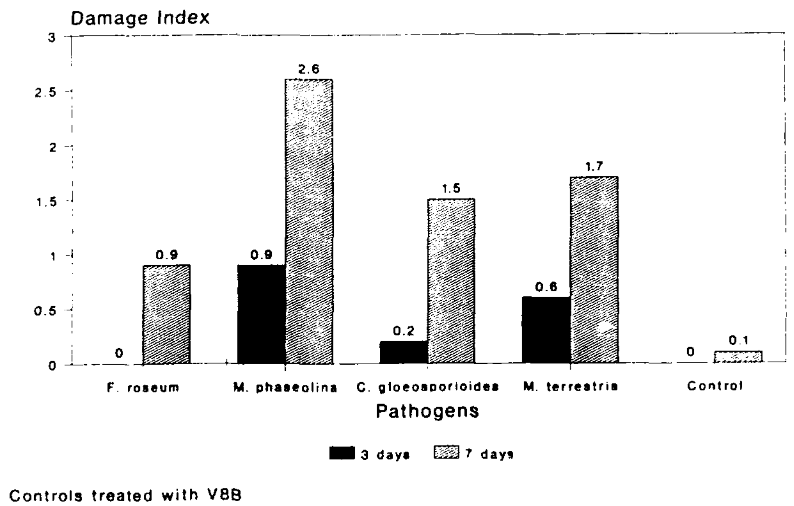


Figure 4. Impact of selected pathogens on milfoil at days 3 and 7

Summary and Conclusions

The rapid screening bioassay resulted in the identification of ten new potential pathogens on hydrilla and nine new potential pathogens on milfoil.

In the case of milfoil, if the questionable binding of *Colletotrichum* is dismissed as a false positive, a pattern identical to that seen in the hydrilla assays likewise suggests that the absence of lectin-mediated specific recognition of the pathogen is likely to result in measurable pathogenesis, at least in an opportunistic scenario such as this where plant defense integrity has been compromised. Therefore, although lectins do appear to have a role in the specific association of microbes to host plants, that association, based on these preliminary data, somehow confers immunity to pathogenesis by that microbe.

References

Barkai-Golan, R., Mirelman, D., and Sharon N. 1978. Studies on growth inhibition by lectins of penicillia and aspergilli. *Archives of Microbiology* 116:119.

Dazzo, F., and Hubbell, D. 1975. Cross-reactive antigens and lectin as determinants of symbiotic specificity in the *Rhizobium*-clover association. *Applied Microbiology* 30:1107.

Mirelman, D., Galun, E., Sharon, N., and Lotan, M. 1975. Inhibition of fungal growth by wheat-germ agglutinin. *Nature* 256:414.

Smart, R. M., and Barko, J. W. 1985. Laboratory culture of submersed freshwater macrophytes on natural sediments. *Aquatic Botany* 21:251.

Smith, C. S., Chand, Tara, Harris, Robin F., and Andrews, John H. 1989. Colonization of a submersed aquatic plant, Eurasian watermilfoil, by fungi under controlled conditions. *Applied and Environmental Microbiology* 55:2326.

Theriot, E. A. 1987. Management of aquatic plants with genetically engineered microorganisms; Phase I: Candidate selection. Pages 33-37 in *Proceedings, 21st Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-87-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Theriot, E. A., and Kees, S. L. 1989. Genetic Engineering: Host Specificity. Pages 64-70 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Biotechnical Approaches to Aquatic Plant Management: Allelopathy

Influence of Various Aquatic Plant Extracts on the Growth of *Hydrilla verticillata* Royle

by

Harvey L. Jones[1] *and Stewart L. Kees*[1]

Introduction

The term allelopathy was first coined by Molisch in 1937. Specifically, allelopathy refers to the biochemical interactions that take place among plants, but its effectiveness depends on the addition of a chemical to the environment (Sutton 1986a). In general, the term allelopathy refers to the detrimental effects of higher plants of one species (the donor) on the germination, growth, or development of another species (the recipient) (Putnam 1985).

Rice (1974) provided a more functional definition of allelopathy, which is taken to mean any direct or indirect harmful effect by one plant (including microorganisms) on another through production of chemical compounds that escape into the environment. Similarly, Parker (1984) defined allelopathy as the harmful effect of one plant or microorganism on another owing to the release of secondary metabolic products into the environment.

Allelopathy is a potentially important mechanism in fighting the war against undesirable nuisance weed problems. Studies have shown that some plants have the capability of eradicating other species in the same area; however, most of these studies have been conducted using terrestrial plants or plants located in the littoral zone of aquatic habitats.

The purpose of this research effort was to conduct experiments to determine potential candidate aquatic plants that would reduce the growth, reproduction, and/or distribution of the aquatic hydrophyte *Hydrilla verticillata* using bioassays. Bioassays are a first step in determining allelopathic potential. Test tube assays were used as a rapid screening method to indicate the allellopathic potential of various candidates. Through laboratory bioassays, Elakovich and Wooten (1989) listed several aquatic plants that have the allelopathic potential to reduce or inhibit the growth of other species.

There are few studies that show the allelopathic effects of submersed aquatic hydrophytes.

Methods and Materials

Test tube bioassays were conducted in the greenhouse in a circulated waterbath at a constant temperature of 25° C. The objective of this research effort was to test a number of aquatic plants for their ability to reduce the growth, reproduction, and/ or distribution of the hydrophyte *Hydrilla verticillata.* Procedures used in this study were modified from Elakovich and Wooten (1989).

Test species selection

Species selected for analysis were based on reports of potentially allelopathic hydrophytes found in pertinent literature reviews and the publications of Elakovich and Wooten (1989). In the study reported herein,

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

the species selected were examined for their allelopathic potential to impact the growth of the target species *Hydrilla verticillata*. A list of selected species is given in Table 1.

Table 1
Plant Species (and Plant Parts) Used as Plant Extracts in the Hydrilla Assay

Common Name	Scientific Name	Plant Part
A Pondweed	*Potamogeton nodosus* Poir.	1
B Fanwort	*Cabomba caroliniana* Gray var.	1
C Common water nymph	*Najas guadalupensis* (Spreng.)	1
D Eelgrass	*Vallisneria americana* Michx.	1
E American lotus	*Nelumbo lutea* (Willd.) Pers.	roots
F American lotus	*Nelumbo lutea* (Willd.) Pers.	stems & leaves
G Duck-potato	*Sagittaria lancifolia* L.	stems & leaves
H Coontail	*Ceratophyllum demersum* L.	1
I Eurasian watermilfoil	Myriophyllum spicatum	1
J Fragrant water-lily	*Nymphaea odorata* Aiton	stems & leaves
K Duck-potato	*Sagittaria lancifolia* L.	roots
L Pickerelweed	*Pontederia lanceolata* Nutt.	stems & leaves

[1] Entire plant used as the extract.

Plant collection

Aquatic plants were field collected from Caddo Lake, Louisiana, and J. D. Murphee Wildlife Refuge, Port Arthur, Texas, and transported back to Vicksburg, MS, in ice chests with sufficient ice to keep the plants from deteriorating. Entire plants were collected whenever possible. Plants were washed to remove dirt and debris, and allowed to drip to remove excess water.

Hydrilla stock cultures

Axenic cultures were grown from hydrilla tubers and turions obtained from greenhouse grown plants. Tubers were thoroughly washed to remove mud and sand, and sterilized in 50 percent bleach for 15 min. The tubers were then rinsed in deionized water and for 10 min in 10 percent bleach. Cultures were grown in three 8-L-capacity nalgene cylinders in 6 L of artificial lake water (ALW) medium, a carbonate-buffered growth medium derived from Gerloff medium (Smith and Jones 1988). The cylinders (each containing 25 to 35 tubers) were aerated with compressed air. The plants were grown for approximately 3 weeks, then clipped to 11 cm from the apical tips and recultured.

Extract preparation

Two hundred grams of each of the test plants was cut into small pieces, placed in a Waring commercial blender to which 200 ml of reverse osmosis water was added, and blended for 5 min on low speed and for 2 min on high speed. Each of the 200-g aliquots was refrigerated for 24 to 72 hr to enhance extraction of the organic compounds. The aliquots were centrifuged at 10,000 rpm for 10 min in a refrigerated centrifuge (Beckman J2-21M/E), and then filtered through Whatman no. 54, 42, and GF/F filter papers, respectively. The filtrate was frozen until all plants to be tested were processed.

Initial dry weights

Mature *Hydrilla verticillata* grown from axenic cultures were cut to 2 cm from the apical tip. Ten explants were randomly selected for initial dry weight determination, placed in aluminum foil, and dried at 70° C for 1 week; the weights were then recorded.

Aeration

Into each test tube was inserted a no. 4 rubber stopper (with two holes), into which two pieces of glass tubing were inserted for aeration. One piece of glass tubing extended from the bottom of the test tube to approximately 1 in. above the stopper; the other piece tubing, approximately 2 in. long, extended the same distance out of the stopper.

The long glass tubing had a piece of tygon tubing attached (1 in. long), to which a hypodermic needle was attached. The long piece of flexible tubing was attached to each needle and then to a central compressed-air source to provide aeration to all test tubes (Figure 1).

Experiment 1. One 2-cm-long apical tip explant of *Hydrilla verticillata* (axenic cultures) was placed in each of the eighty 90-ml-capacity test tubes with 50 ml of ALW medium (personal communication, Dr. Craig Smith). Experimental cultures were randomly selected to receive 10 ml of one of the test plant extracts (Table 1). Test tubes were numerically arranged in test tube racks with a vacant space on each side. Numbered aeration plugs were inserted in the test tubes, and compressed air was supplied to each tube. Five replicates of each test plant extract were used in this study, in addition to 10 controls, each of which contained an additional 10 ml of ALW media in lieu of test plant extracts.

Figure 1. Experimental setup for hydrilla test tube growth bioassay

Plants were grown for 14 days and then harvested. After the plant length and health status were recorded, the plants were placed in aluminum foil and dried at 70° C for 7 days. The plant weight was then recorded.

Experiment 2. Experiment 1 was repeated, and the data were verified.

Experiment 3. Experiment 3 involved the determination of the minimum critical dosage of extract required to produce a significant reduction in hydrilla biomass based on the results from Experiments 1 and 2. The first phase of Experiment 3 evaluated the effects of the 1-ml concentration of plant extracts on hydrilla biomass production.

Data analysis

The data were subjected to Analysis of Variance and the Duncan's Multiple Range Test to determine if there were significant differences between the controls and test species.

Results

In Experiment 1 (Figure 2), all extracts were significantly different from the controls; however, *Vallisneria americana* and *Najas guadalupensis* appeared to increase hydrilla biomass. *Potamogeton nodosus* extract failed to significantly increase or decrease hydrilla biomass; *Ceratophyllum demersum* showed the greatest reduction of hydrilla biomass.

The Experiment 2 results confirmed the results of Experiment 1; for the second time, *Ceratophyllum demersum* produced the greatest reduction of hydrilla biomass.

Experiment 3 (Figure 3) results showed that, again, *Ceratophyllum* extract had the greatest impact on hydrilla biomass reduction, and *Potamogeton* produced comparable results. These two plant extracts were the only species that exhibited significant differences in reduction of hydrilla biomass at the 1-ml concentration.

Conclusions

Based on these preliminary data, *Ceratophyllum* is considered our best potential allelopathic candidate for hydrilla. However, several other species warrant additional attention because they were borderline allelopathic during phases of our study. These species include *Vallisneria americana, Najas guadalupensis,* and *Potamogeton nodosus,* in addition to *Eleocharis coloradoensis* (spikerush) because it has been found to be allelopathic

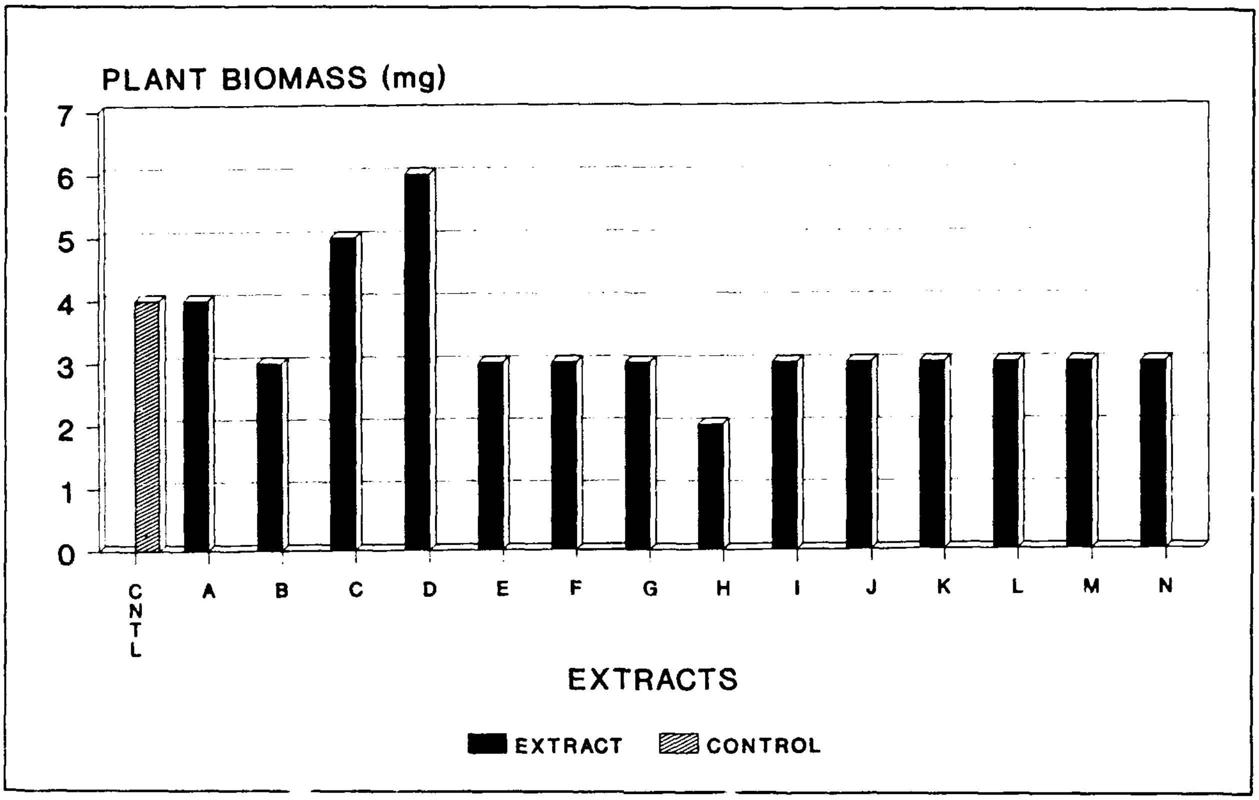


Figure 2. Influence of plant extracts on growth of hydrilla at the 10-ml concentration

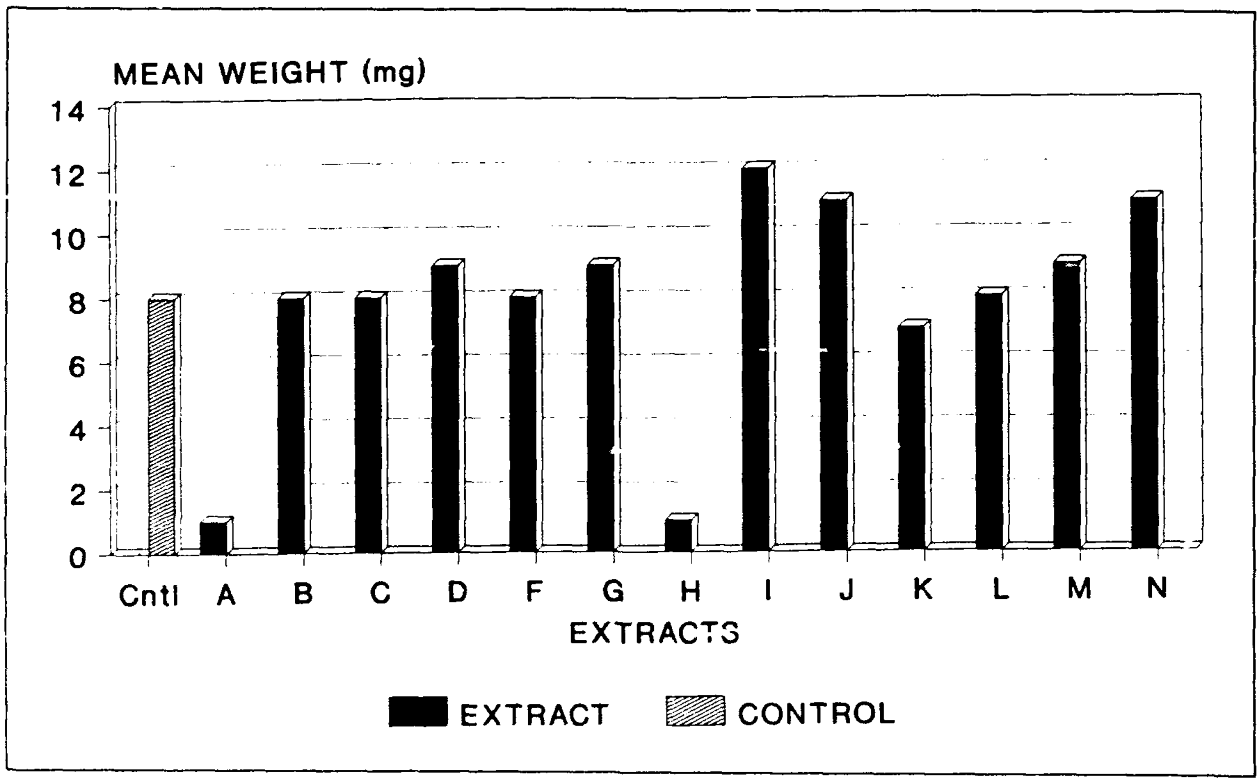


Figure 3. Influence of plant extracts on growth of hydrilla at the 1-ml concentration

to several aquatic species. When grown in established stands of spikerush, hydrilla biomass production was decreased by 85 to 90 percent when compared to hydrilla plants grown alone (Sutton 1986b)

Experiment 3 (at the 1-ml concentration) will be repeated to verify the observed activity of *Potamogeton* noted at this concentration but not at the 10-ml concentration.

Future Work Planned

The next step in this research effort is to conduct test tube assays of all extracts at various concentrations with *Myriophyllum spicatum* as the target species. Rooted plant studies will be conducted using the extracts found to be most allelopathic in the test tube assays against hydrilla and watermilfoil.

Acknowledgments

The authors wish to acknowledge Dr. Jean Wooten, Dr. Craig Smith, Mrs. Debra Dent, Mrs. Ramona Warren, and Messrs. William Boyd and Dennis Brandon for invaluable assistance in statistical data analysis, graphics preparation, and technical reviews.

References

Elakovich, S. D., and Wooten, J. W. 1989. Allelopathic potential of sixteen aquatic and wetland plants. *Journal of Aquatic Plant Management* 27:78-84.

Parker, Sybil P., ed. 1984. *McGraw-Hill Dictionary of Scientific and Technical Terms,* 3rd ed. McGraw-Hill, New York.

Putnam, A. R. 1985. Allelopathic research in agriculture: Past highlights and potential. Pages 1-8 in *The Chemistry of Allelopathy: Biochemical Interactions Among Plants.* A. C. Anderson, ed. ACS Symp. Series 268. The American Chemical Society, Washington, DC.

Rice, E. L. 1974. *Allelopathy.* Academic Press, New York.

Smith, C. S., and Jones, H. L. 1989. Inhibition of hydrilla growth by plant extracts and secondary compounds. Pages 91-98 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sutton, D. L. 1986a. Notes: Influence of allelopathic chemicals on sprouting of hydrilla tubers. *Journal of Aquatic Plant Management* 24:88-90.

Sutton, D. L. 1986b. Growth of hydrilla in established stands of spikerush and slender arrowhead. *Journal of Aquatic Plant Management* 24:16-20.

Biological Control of Waterlettuce Using Insects: Past, Present, and Future

by
Michael J. Grodowitz[1]

Introduction

Waterlettuce, *Pistia stratiotes* L., is a free-floating aquatic plant from the Araceae or Arum family (Figure 1). It is characterized by having a relatively short stem where the leaves attach in whorls. The plant has a distinctive light yellow-green to gray-green coloration. The leaves are covered with a fine pubescence and are typically enlarged basally by the formation of air-filled aerenchyma cells. This enlargement and the well-developed root

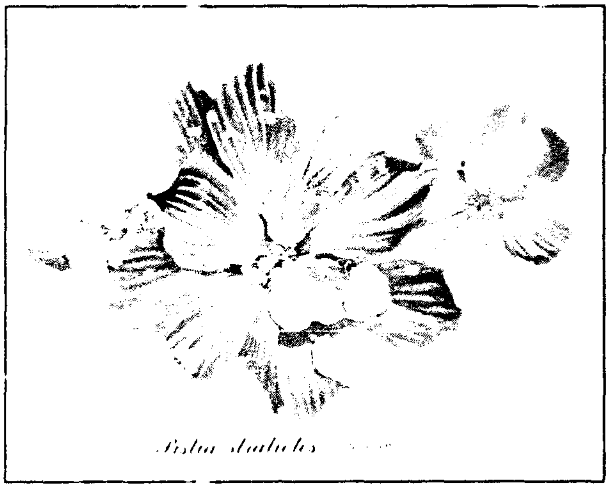


Figure 1. Waterlettuce, Pistia stratiotes L.

system work together to maintain plant buoyancy. While the majority of reproduction occurs vegetatively, in which daughter plants are produced via stolons, sexual reproduction is now known to occur in the United States (Dray and Center 1989). The plant has one of the highest productivity rates, and minimal numbers of plants can quickly cover an entire water body.

The plant can be found in most slow-moving or stagnant water bodies, including canals, bayous, streams, ponds, and lakes. In the United States, waterlettuce usually forms dense floating mats where individual plants are highly intertwined, forming an almost impenetrable barrier.

Waterlettuce is widely distributed in many tropical and semitropical regions of the world (Holm et al. 1977). These include portions of Africa, southern Asia, the southern United States, the southern portion of central and South America, as well as the Caribbean.

The plant's extreme cold intolerance appears to severely limit its distribution in the more temperate regions. For example, in the United States, waterlettuce is limited to only the southern portions of Florida, Louisiana, and Texas (Figure 2).

The high productivity of waterlettuce and its ability to form large impenetrable floating mats can cause many problems (Holm et al. 1977). For example, navigation is severely curtailed on water bodies containing large infestations of waterlettuce. This, in turn, can reduce recreational uses. Waterlettuce can block water intake valves from which industrial and local municipalities receive water supplies.

In addition, water losses appear to be higher where waterlettuce infestations occur because of increased evaporation and transpiration through the leaf surfaces. Waterlettuce has also been shown to impact aquatic or semiaquatic agriculture, including rice (Bua-ngam and Mercado 1975).

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

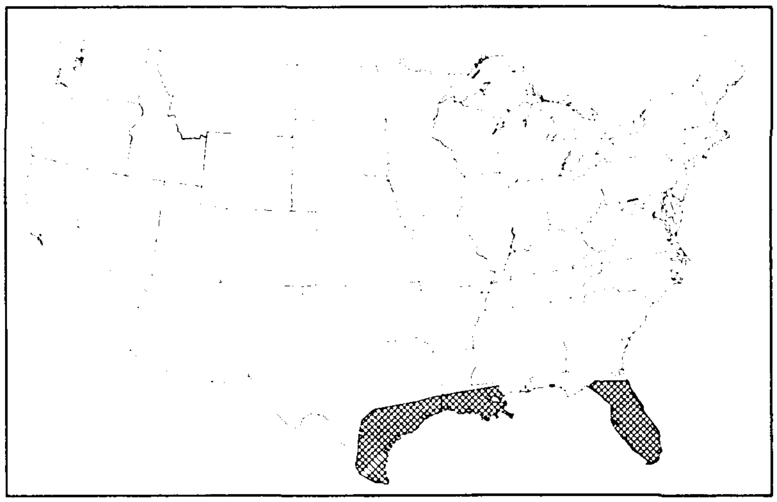


Figure 2. Distribution of waterlettuce in the United States

Distinct changes in water quality have also been documented in areas beneath or near waterlettuce mats (Attionu 1976). These include lowered pH and dissolved oxygen. Such changes in water quality have a significant impact on local fish populations.

Another economically important problem caused by the presence of waterlettuce is the formation of ideal mosquito-breeding habitat (Holm et al. 1977). While other floating aquatic plants serve in this capacity, waterlettuce apparently attracts high numbers of species capable of disease transmission. For example, waterlettuce infestations harbor species of the genera *Mansonia* and *Anopheles*. Several species in these genera have been shown to transmit the causative agents for malaria, encephalomyelitis, and rural filariasis.

Harborage is not the only manner in which waterlettuce increases population levels of mosquitoes. It also serves as a means for *Mansonia* sp. larvae to acquire oxygen from the root system.

Because of the manifold problems associated with waterlettuce infestations, researchers began during the 1970's to search for viable alternatives to more traditional methods for the control of waterlettuce. One alternative identified was the use of insect biocontrol agents. The following is a short historical account of the advances made to date in the use of insect biocontrol agents on waterlettuce in the United States, including a discussion of possible future directions.

The Classical Biocontrol Approach

A classical biological control approach has been followed for the management of waterlettuce using insect biological control agents (Figure 3). Such an approach can be viewed as a pipeline, with different sections of the pipe corresponding to various facets of the research that are involved in identifying, testing, and releasing exotic insect biocontrol agents.

Classical biocontrol typically entails using host-specific insect species from the original host range of the target plant. After suitable candidates are identified overseas, they are subjected to a series of rigorous host-specificity tests at both overseas and US quarantine facilities to ensure that they feed and reside only on the target plant species. After the host-specificity testing has been completed, a petition is sent to the Technical Advisory Board requesting permission for release of the organism into the United States. After the preliminary field tests in the United States have been completed and the efficacy of the agents has been ascertained, the technology involved in the agent's use is transferred to appropriate action organizations.

Coincidental to the overseas and quarantine testing, native or naturalized insects are identified, and their effects on the target plant are determined. Such information on already existing impacts to waterlettuce populations is important because it allows researchers (1) to identify damage caused by native herbivorous insects, as opposed to that caused by the released exotic organisms, and (2) to adequately separate and quantify the impact caused by both native and exotic insect biocontrol agents.

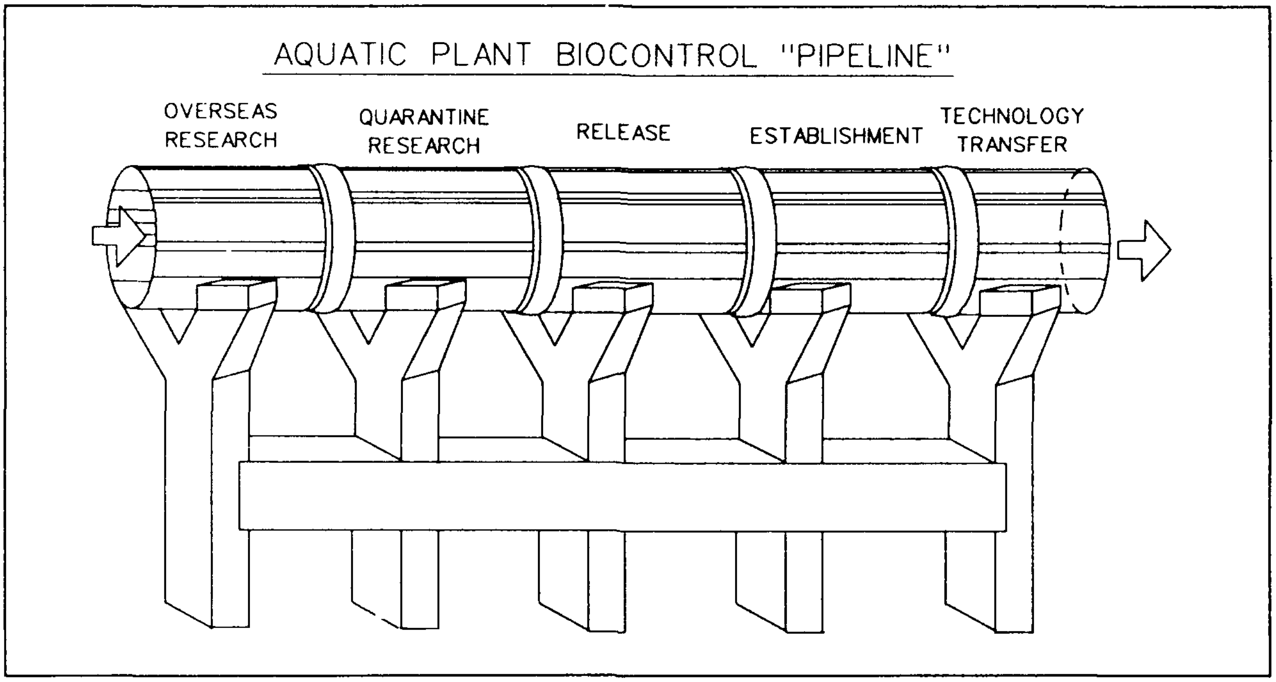


Figure 3. Classical biological control "pipeline" approach used by researchers of the Corps of Engineers and the USDA-ARS for management of waterlettuce

Another essential facet of the classical approach is understanding the biology of both the insect biocontrol agents and their host plant, i.e., foundational research. Such studies strengthen and support the overall biocontrol program. Examples of foundational research include taxonomic studies of the exotic organisms, characterization of the mechanisms involved in host plant impact, and life history studies.

These studies work together to strengthen and support the pipeline from one section to another. Such an overall approach to biocontrol of waterlettuce minimizes the risk of releasing nonspecific organisms, increases the chances of using highly effective insect agents, and allows for the ability to separate impact due to native insects from that caused by the introduced species.

Native Insects

As indicated previously, an important first step before releasing any exotic insect biocontrol agents is documenting the impacts of native or naturalized insect species on the target plant species. Toward this goal, USDA-ARS researchers of the Aquatic Plant Research Laboratory in Fort Lauderdale, FL, initiated in 1986 a detailed survey to determine numbers and kinds of insect species feeding on waterlettuce in the Florida area (Dray et al. 1988).

Plants from 66 sites were examined for signs of insect feeding, and more than 47,000 organisms were collected. The majority of organisms collected (>70 percent) were *Hyallela azecta*, an amphipod that apparently does little if any damage to waterlettuce. The next most abundant group contained species within the order Diptera, or flies. Within this order of insects, the families Chironomidae (midges) and Ceratopogonidae (no-see-em's) represented >15 percent of the total collection.

No evidence was collected to indicate that the species *H. azecta* has any impact on waterlettuce infestations. However, nine insect species were identified as being "important," i.e., causing some quantifiable degree of damage to waterlettuce (see following tabulation).

Lepidoptera (moths and butterflies)
Samea multiplicalis *Synclita obliteralis* *Spilosoma virginica* *Petrophila drumalis*
Curculionidae (weevils)
Tanyspyrus lemnae *Stenopelmus rufinasus*
Homoptera (aphids and leafhoppers)
Draeculacephala inscripta *Rhopalosiphum numphaeae* Pseudococcidae

Two species were found to significantly impact waterlettuce: the moths *S. multiplicalis* and *S. obliteralis*. These species evidently can both feed and develop entirely on waterlettuce (Knopf and Habeck 1976; DeLoach, DeLoach, and Cordo 1979). *Samea multiplicalis* has a small- to medium-sized late instar larva that is fairly nondescript. It is pale yellow to creamy white in coloration and feeds by removing the epidermis and underlying tissues from the leaves between and along the prominent veins. Such feeding damage makes the leaves appear "shredded."

Synclita obliteralis differs from *Samea multiplicalis* in that it typically resides within a "sandwich" of small leaf pieces that it cuts from leaf edges. The leaves of waterlettuce infested with *S. obliteralis* usually have large, roundish holes, due to the insect's specific case-making and feeding behaviors.

While large populations of *S. multiplicalis* and *S. obliteralis* have been documented with resulting high damage to the leaf surfaces, they typically have little if any actual impact to waterlettuce population levels. Little information is available on why they are unable to successfully impact total population levels.

The remaining "important" species are most likely transient species that do not usually feed on waterlettuce. For example, the two weevil species (*Tanyspyrus lemnae* and *Stenopelmus rufinasus*) are known to feed and develop on *Lemna minor* and *Salvinia* sp., respectively.[1] As these weevil species are most likely transient, the most likely reason for their appearance on waterlettuce is that both *L. minor* and *Salvinia* sp. are often found in association with waterlettuce. Both insect species have been observed to feed on waterlettuce, although the damage was relatively minor as compared with that of the moth species.

The surveys also documented that large numbers of *Draeculacephala inscripta* (leafhoppers) and *Rhopalosiphum nymphaeae* (aphids) are common, and individuals of the family Pseudococcidae (mealybugs) are sometimes found. Only minimal feeding damage due to these species has been observed. These two insect species are of importance because they may be involved in plant disease transmission. Other closely related species have been implicated in disease transmission for various plant species (Borror, DeLong, and Triplehorn 1981).

Exotic Insect Species

Neohydronomus affinis

During the early 1970's, researchers in Argentina identified a potential candidate for the biological control of waterlettuce, the weevil *Neohydronomus affinis* Hustache (DeLoach, DeLoach, and Cordo 1976). After completing considerable work on the insect's basic biology and efficacy, these researchers concluded that it was ideal for use as a biocontrol agent.

Adult *N. affinis* are small weevils (ca. 1.8 mm in length) that make small roundish holes in the leaf surface during feeding (DeLoach, DeLoach, and Cordo 1976). Large quantities of feeding give the leaves the appearance of being "peppered with buckshot."

Large numbers of adults have been shown to cause plant death. The adults often enter these feeding scars and reside within the spongy internal cellular layer of the leaf. The adults deposit eggs in shallow feeding

[1] Personal Communication, 1990, C. O'Brien, Florida A&M University, Tallahassee.

scars just beneath the leaf surface. The emerging larvae tunnel through the leaf, allowing for further plant deterioration. Larvae are seldom seen emerging from the internal cell layers. The larvae pupate within the internal cellular layers of the leaf.

Researchers from the Commonwealth Scientific and Industrial Research Organization imported *N. affinis* into Australian quarantine in 1981 (Harley et al. 1984) and made field releases the following year. Waterlettuce reductions of 100, 93, and 82 percent were achieved at three reservoirs in only 20 months.

Using information on host specificity gained in Australia, *N. affinis* was brought into US quarantine in 1985. Building upon the host-specificity testing done by the Australians, US testing was finished relatively rapidly, and permission to field test *N. affinis* was subsequently obtained in 1987 (Habeck and Thompson, in preparation).

The first release of *N. affinis* in the United States occurred at Kreamer Island on Lake Okeechobee (Palm Beach County), Florida, during April 1987 (Dray et al. 1990). Approximately 2,300 individuals were released during the period April 1987 to January 1988. Additional releases followed, and to date, *N. affinis* has been released at more than 80 sites throughout Florida (Center and Dray, in preparation).

Neohydronomus affinis population dynamics and changes in waterlettuce levels appear to be correlated. For example, at Kreamer Island, only minimal numbers of *N. affinis* occurred for the first 20 months after the initial release. During these 20 months, percent plant coverage typically remained at between 60 and 90 percent. However, with subsequent increases in *N. affinis* population numbers during January 1989 through May 1990, significant decreases in plant coverage resulted. Waterlettuce coverage remains below 5 percent at this site (Dray et al. 1990).[1] To date, waterlettuce has been eliminated from three of the four initial Florida release sites.

Namangana pectinicornis

Namangana pectinicornis is another insect species with high potential as an effective biocontrol agent of waterlettuce. Beginning in 1963, several researchers identified *N. pectinicornis* as an ideal candidate for biocontrol of waterlettuce, based on its high degree of host specificity and damaging effects to waterlettuce (George 1963; Mangoendihardjo and Nasroh 1976; Alam, Alum, and Ahmed 1980).

Namangana pectinicornis is a relatively large moth having a wing span ranging from 16 to 20 cm. It is mostly brown, with minimal markings. Larvae feed on the leaf tissues and have been shown to cause considerable damage. In addition, the pupa is located in the internal portion of the leaf and, in the process of formation, also damages the plant (Habeck and Thompson, in preparation).

In 1986, *N. pectinicornis* was introduced into US quarantine for further host-specificity testing (Habeck and Thompson, in preparation). *Namangana pectinicornis* was subsequently released from quarantine during October 1990. Currently, researchers at the USDA-ARS Aquatic Plant Management Research Laboratory in Fort Lauderdale, FL, are maintaining laboratory-reared colonies for eventual releases during 1991.

Louisiana and Texas Surveys

During the spring and summer of 1990, extensive surveys of waterlettuce were conducted throughout the plant's distribution in Louisiana and Texas. These surveys, which were similar to those conducted in Florida during 1986 (Dray et al. 1988), were for the primary purpose of determining what native herbivorous insect species were impacting waterlettuce populations. The surveys were

[1] Personal Communication, 1990, F. A. Dray, USDA-ARS, Aquatic Plant Management Laboratory, Fort Lauderdale, FL.

considered an important step prior to the release of *N. affinis* in these areas.

Seven of the nine "important" species found in Florida were collected from sites in Louisiana and Texas. The species that were not collected included *Petrophila drumalis* and specimens from the family Pseudococcidae (mealybugs). Additional collection efforts may reveal the presence of these species in the Louisiana and Texas areas.

Surprisingly, *N. affinis* was collected in relatively high densities (70 individuals/m^2) from several sites in southeastern Louisiana (Figure 4). This was not expected since *N. affinis* was never officially released in this area, and limited collecting efforts by other researchers in the past did not reveal the presence of *N. affinis* in this area.

The survey sites where *N. affinis* was collected occurred within an approximate 50-mile diameter from Lake Verret to east and south of Lake Beouf. No *N. affinis* was collected from any sites west of the Atchafalaya Basin. The relatively high densities of *N. affinis* indicate that the population may have been present in this area for at least 1 to 2 years, based on information on population dynamics after initial releases observed at Australia and Florida sites.[1]

Reasons for the presence of *N. affinis* in these areas are only speculative. Possible explanations include the following: (1) *N. affinis* populations were already established in Louisiana prior to the Florida releases, (2) *N. affinis* migrated from Florida sites naturally, or (3) infested plants from Australia or some other country were distributed into this area.

Little credence can be given to these explanations, however. For example, past collections by researchers during the early 1960's in the west Louisiana and east Texas area did not reveal the presence of *N. affinis*. Hence, it is difficult to believe it was present in the United States prior to its release in Florida.

While *N. affinis* can disperse relatively rapidly from original release sites, the large distances covered (i.e., from Florida to Louisiana) in such short time periods are unrealistic, especially considering the lack of substantial waterlettuce populations in the panhandle of Florida and the extreme southern portions of Alabama and Mississippi to aid in their distribution.

Similarly, the odds of infested plants reaching Louisiana intact from Australia or South America is low.

The most plausible explanation is that plants infested with *N. affinis* from Florida release sites were accidentally distributed into this area. However, even this explanation has limited grounds for complete acceptance. For example, the number of release sites with significant population densities of *N. affinis* was still low at Florida sites during 1988 and 1989 (Dray et al. 1990). Infested plants would have had to been transported into Louisiana during this period for insect densities to reach such high levels by the summer of 1990. Hence, the odds of removing infested plants from Florida with sufficient densities at that time would be low. Reasons for the presence of *N. affinis* in Louisiana are still being considered.

Future Directions

Overall, the future looks promising with regard to the use of insect biocontrol agents for management of waterlettuce in the United States. With the relatively short effect time to control that has occurred for several Florida sites, *N. affinis* appears to be highly effective. In addition, with the release of *N. pectinicornis* from quarantine, another agent will soon be in use, one that apparently attacks the plant from an altogether different vantage point than *N. affinis*.

---

[1] Personal Communication, F. A. Dray, USDA-ARS, Aquatic Plant Management Laboratory, Fort Lauderdale, FL.

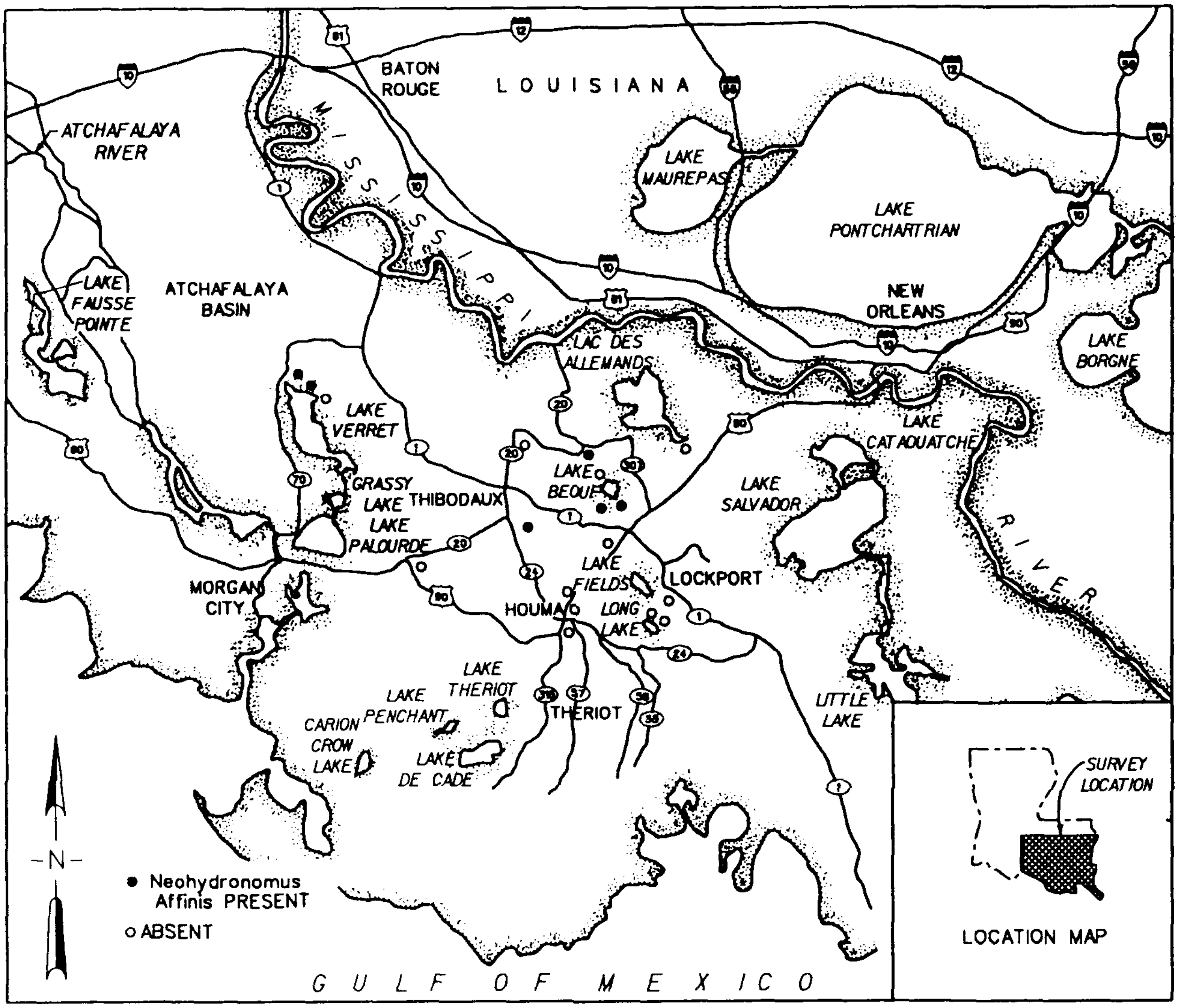


Figure 4. Survey sites in southeastern Louisiana at which N. affinis was collected during summer 1990

More specifically, in the immediate future, efforts will continue to enlarge the distribution of *N. affinis* in the US waterlettuce range. This will be accomplished by moving infested plants in the Florida and Louisiana areas to areas where *N. affinis* is not currently present. Laboratory-reared individuals will be used to supplement such range extensions whenever possible.

Efforts will also continue to monitor *N. affinis* populations dynamics, and to correlate these with shifts in waterlettuce infestation levels. A new release of *N. affinis* is scheduled for southeast Texas during the spring and summer of 1991, with subsequent monitoring of the insect's effects. Whenever possible, detailed quantification of insect and plant populations will be accomplished.

In October 1991, *N. pectinicornis* was officially released from US quarantine facilities. Efforts will be made to release this insect into south Florida sites no later than spring of 1991. *Namangana pectinicornis* is a relatively large moth capable of inflicting great damage on waterlettuce (Habeck and Thompson, in preparation). Greenhouse studies have indicated that it is highly effective in producing damage. Future plans include

releasing *N. pectinicornis* at several south Florida sites with subsequent monitoring of population levels and efficacy. If this species proves effective at the initial release sites, larger scale range extensions will be attempted.

References

Alam, S., Alum, M. S., and Ahmed, M. S. 1980. Notes on *Athetis pectinicornis*, a species of waterlettuce and waterhyacinth in Bangladesh. *International Rice Research Newsletter* 5:15.

Attionu, R. H. 1976. Some effects of water lettuce (*Pistia stratiotes* L.) on its habitat. *Hydrobiologia* 50:245-255.

Borror, D. J., DeLong, D. M., and Triplehorn, C. A. 1981. *An Introduction to the Study of Insects*. Saunders College Publishing, Philadelphia, PA.

Bua-ngam, T., and Mercado, B. L. 1975. The life cycle of water lettuce (*Pistia stratiotes* L.). *Philippine Weed Science Bulletin* 2:11-15.

Center, T. D., and Dray, A. F. Biological control of *Pistia stratiotes* L. (waterlettuce) using *Neohydronomus affinis* Hustache (Coleoptera: Curculionidae). Technical Report (in preparation). US Army Engineer Waterways Experiment Station, Vicksburg, MS.

DeLoach, C. J., DeLoach, A. D., and Cordo, H. A. 1976. *Neohydronomus affinis*, a weevil attacking *Pistia stratiotes* in South America: Biology and host specificity. *Annals of the Entomological Society of America* 60:830-834.

DeLoach, C. J., DeLoach, A. D., and Cordo, H. A. 1979. Observations on the biology of the moth, *Samea multiplicalis*, on waterlettuce in Argentina. *Journal of Aquatic Plant Management* 17:42-44.

Dray, F. A., and Center, T. D. 1989. Seed production by *Pistia stratiotes* L. (waterlettuce) in the United States. *Aquatic Botany* 33:155-160.

Dray, A. F., Center, T. D., Habeck, D. H., Thompson, C. R., and Balciunas, J. K. 1988. A survey of the fauna associated with *Pistia stratiotes* L. (waterlettuce) in Florida. Technical Report A-88-6. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dray, F. A., Center, T. D., Habeck, D. H., Thompson, C. R., Cofrancesco, A. F., and Balciunas, J. K. 1990. Release and establishment in the southeastern United States of *Neohydronomus affinis* (Coleoptera: Curculionidae), an herbivore of waterlettuce. *Journal of Environmental Entomology* 19:799-802.

George, M. J. 1963. Studies on infestation of *Pistia stratiotes* Linn. by the caterpillar of *Namangana pectinicornis* Hamps., a noctuid moth, and its effects on *Mansonia* breeding. *Indian Journal of Malariology* 17:149-155.

Habeck, D. H., and Thompson, C. R. Host specificity and biology of the weevil *Neohydronomus pulchellus*, biological control agent of waterlettuce (*Pistia stratiotes*). Technical Report (in preparation). US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Harley, K. L. S., Forno, I. W., Kassulke, R. C., and Sands, D. P. A. 1984. Biological control of water lettuce. *Journal of Aquatic Plant Management* 22:101-102.

Holm, L. G., Plucknett, J. V., Pancho, J. U., and Herberger, J. P. 1977. *The World's Worst Weeds: Distribution and Biology*. University Press of Hawaii, Honolulu.

Knopf, K. W., and Habeck, D. H. 1976. Life history and biology of *Samea multiplicalis*. *Journal of Environmental Entomology* 5:539-542.

Mangoendihardjo, S., and Nasroh, A. 1976. *Proxenus* sp. (Lepidoptera: Noctuidae), a promising enemy of waterlettuce (*Pistia stratiotes* L.). *Proceedings, 5th Asian-Pacific Weed Science Society Conference,* October 5-11, 1975, Tokyo, Japan.

Movements and Habitat Utilization of Triploid Grass Carp in Lake Marion, South Carolina

by

Samuel J. Chappelear,[1] *Jeffrey W. Foltz,*[1] *Keevin T. Chavis,*[1] *James P. Kirk,*[2] *and K. Jack Killgore*[3]

Introduction

Lake Marion, South Carolina, is a 44,000-ha impoundment composed of open water as well as dense cypress swamps. Aquatic vegetation has become a serious problem in upper Lake Marion north of the Interstate 95 bridge (Inabinette 1985). Upper Lake Marion's shallowness is conducive to aquatic plant growth. Many areas of the lake have limited access due to dense aquatic vegetation. This has hampered use of the lake by recreational hunters and anglers. Herbicides have been used extensively to control the vegetation problem, but a more feasible and long-term solution is needed. Mechanical removal and herbicide treatment can be costly and time consuming, and work only on a limited basis for a limited time.

One possible solution is the release of triploid grass carp (*Ctenopharyngodon idella*). Grass carp have been effective in eliminating *Hydrilla verticillata* in several large lakes in Florida (Beach et al. 1976; Miley, Leslie, and Van Dyke 1979). Advantages of biological control, such as the use of triploid grass carp, include longevity of the method, constant fish-feeding activity against growing vegetation, low long-term cost, and high effectiveness on selected plants (Sutton and Vandiver 1986).

Between 1989 and 1991, 300,000 triploid grass carp have been or will be released at various locations in upper Lake Marion to control nuisance aquatic vegetation (South Carolina Aquatic Plant Management Council and South Carolina Water Resources Commission 1990).

Water temperature is known to cause migrational movement in grass carp once water reaches 15° to 17° C (Aliev 1976). A rise in water level or increased flow rates has also caused grass carp to exhibit migrational movement (Stanley, Miley, and Sutton 1978). If triploid grass carp were to migrate up the rivers and away from aquatic plant-infested areas, they would be ineffective for weed control.

Objectives of this study were to (1) determine the magnitude and direction of grass carp movements, (2) determine if grass carp remain in the targeted vegetation areas, and (3) examine characteristics of habitats used by triploid grass carp.

Study Site

Lake Marion was formed by impoundment of the Santee River and has an average depth of 5 m and a maximum depth of 12 m. Immediately upstream of Lake Marion, the Santee River is formed by the confluence of the Wateree and Congaree Rivers. The Wateree River originates at the Wateree Dam about 100 km upstream from Lake Marion. The Congaree River originates at the Saluda Dam on Lake Murray and flows 85 km before joining the Wateree.

Average discharge of the Wateree and Congaree Rivers is 183 and 266 m^3/sec, respectively. When Lake Marion was constructed in

[1] South Carolina Agricultural Experiment Station, Clemson University, Department of Aquaculture, Fisheries and Wildlife, Clemson, SC.
[2] South Carolina Wildlife and Marine Resources Department, Columbia, SC.
[3] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

1941, it impounded 6,500 ha in its headwater section, which was known as the Santee Swamp. The swamp is anaerobic most of the year and hence influences water quality in upper Lake Marion (Bates and Marcus 1989).

Vegetated areas of the lake targeted for control have an estimated 4,800 ha of submersed vegetation, mostly upstream from the Interstate 95 bridge. Habitats in upper Lake Marion were categorized as follows: (1) river channel (RC) (Santee, Congaree, or Wateree River), 2 to 8 m deep; (2) open water with creek channels running through (OWCC), 1 to 2 m deep; (3) open water with shallow flats (OWSF), 1 to 2 m deep; (4) thick cypress swamp (TCS), 2 to 3 m deep; and (5) open water with scattered cypress stands (OWCS), 2 to 3 m deep.

All habitat types except the Santee River channel support dense stands of nuisance aquatic vegetation. No assessment of the proportion of upper Lake Marion that each habitat type comprises has been made. Likewise, no assessment of the magnitude of the swamp's influence on downstream water quality has been made, although fish kills due to anaerobic conditions are a common summer phenomenon in upper Lake Marion's swamps.

Methods

Forty-five triploid grass carp were surgically implanted with radio transmitters. The life span of the transmitters was 9 months, and transmitter frequencies ranged from 48.036 to 49.527 kHz. Each fish was identified by a distinct frequency. Fish were anesthetized using a bath containing 100 mg/L MS-222 and 25 mg/L Furacin. Each fish was weighed to the nearest 0.01 kg and measured to the nearest millimeter.

Anesthetized fish were placed in a V-shaped operating trough, so that the fish excluding its abdomen was submersed in water containing MS-222 and Furacin. A small aquarium aerator was used to maintain adequate oxygen levels in the operating trough. A radio transmitter was then surgically implanted using the procedure described by Schramm and Black (1984). Surgical gloves were worn, and instruments and transmitters were disinfected prior to use.

Scales were removed from the incision area, and a 5-cm longitudinal incision was made in the ventral wall, 6 cm anterior to the pelvic girdle. A transmitter was then inserted into the body cavity, and the incision was closed with nonabsorbable silk sutures. Oxytetracycline (50 mg/kg body weight) was injected into the body cavity before the last suture was stitched. Fish were then immediately released into the lake. Approximately equal numbers of fish were released at Pack's Landing, Elliott's Landing, and Santee State Park (Figure 1).

An Advanced Telemetry Systems (model 2000) radio receiver was used. Aerial searches were conducted twice a month to determine the general localities of fish. A trucker whip antenna was mounted on the strut of the plane during aerial searches. Boat searches for implanted grass carp were conducted 2 to 3 days per week for 48 months.

Signals were received while boating with a Telex Communications (model 64 B-S) four-element yagi antenna. Once a signal was picked up by the receiver, the antenna was rotated to ascertain direction, and the boat was motored in that direction. Signal strength increased as the fish was approached. The coax cable was then disconnected from the antenna and dropped in the water beside the boat. Intensity of the signal indicated when the boat was within 25 m of the fish.

Once a fish was located, the date, water depth, and Loran latitude and longitude coordinates were recorded. Water temperature (to the nearest 0.1° C) and dissolved oxygen (to the nearest 0.1 mg/L) were measured at the surface and on the bottom with a YSI dissolved oxygen (DO) meter (model 51B). Mean DO was calculated from the surface and bottom value.

An aquatic vegetation sample was taken from the surface and bottom with a rake.

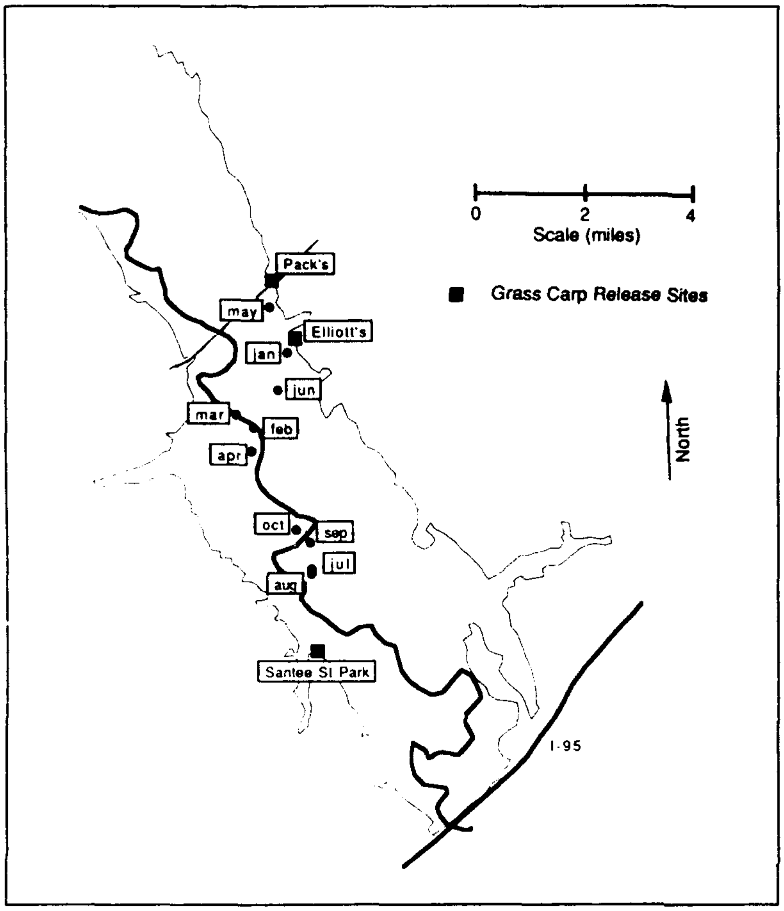


Figure 1. Average ocation of radio-tagged adult triploid grass carp by month in upper Lake Marion, 1989-1990

Aquatic vegetation was identified (Pennwalt Corporation 1984) in the field. The species that comprised the largest proportion of a sample was categorized as primary vegetation, and the species that comprised the next largest proportion was categorized as secondary.

Vegetation density in the vicinity of the fish location was characterized by one of four categories: (1) vegetation covers 50 percent of the surface, (2) vegetation covers 2 percent of the surface, (3) vegetation is present but submersed, or (4) vegetation is sparse. Habitat types were categorized as described above (see heading Study Site).

Fish locations were plotted on a digitized map that indicated the Santee River channel. Days elapsed and distance moved (to nearest 0.01 km) between readings were computed for each fish. Minimum net daily movement was then computed as net kilometers per elapsed days. Linear and nonlinear regressions were employed to describe seasonal changes in minimum net daily movement.

The distance from the river channel to the fish and the width of the reservoir were also computed along a line perpendicular to the fish and the river channel. Distances were recorded to the nearest 0.01 km. Distance of grass carp from the river channel was tested with a t-test (null hypothesis that the distance equals zero). Mean latitude and longitude were computed by month.

Results

Triploid grass carp used in this study averaged 626 mm total length (SE = 11) at the time of release. Of the 51 fish released, 47 were located at least once; the average elapsed time between locations was 10 days. The fish exhibited a general downlake movement from January through October (Figure 1). Grass carp in this study did not demonstrate a preference for the river channel in Lake Marion (Figure 2).

Mean distance of grass carp from the river channel was 1.75 km (SE + 0.08). This mean distance was significantly different from zero (t = 22.84, p = 0.0001). Mean lake width along transects drawn perpendicular to the river channel through each fish location was 5.05 km (SE = 0.06).

Dissolved oxygen levels at fish locations decreased during winter, spring, and summer before increasing in the early fall (Figure 2). The aberration in the curve in Figure 2 was due to extremely low DO levels, which resulted in

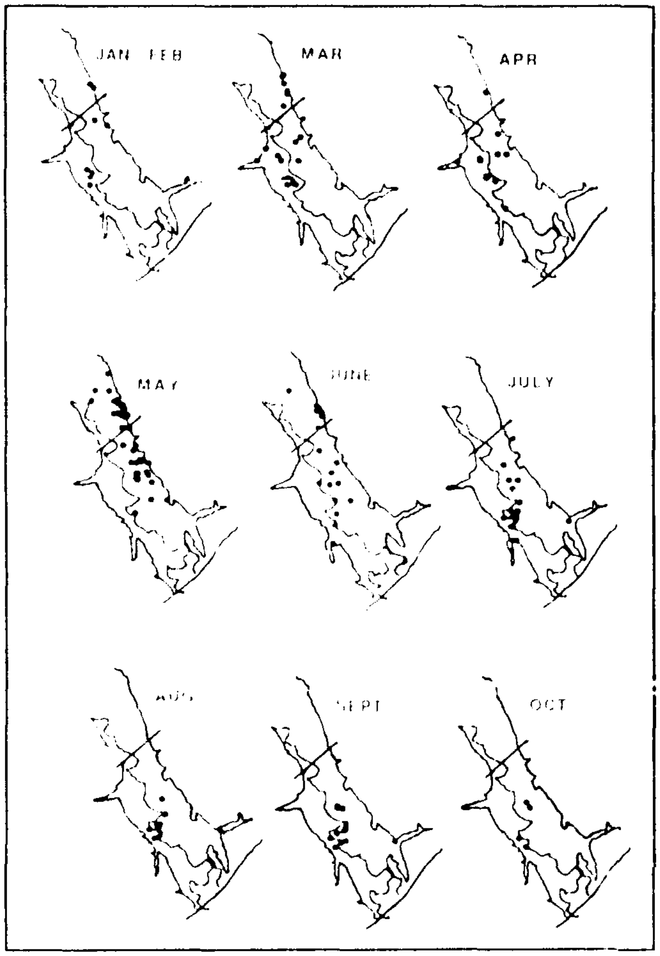


Figure 2. Locations of radio-tagged adult triploid grass carp in upper Lake Marion, 1989-1990. Each dot represents one or more individual fish locations

widespread fish kills in upper Lake Marion on 9 May, 3 June, 15 June, and 22 June 1989. Mean DO concentrations at grass carp locations for the months of June and July 1989 were 3.5 (SE = 0.4) and 4.0 (SE = 0.2) mg/L, respectively, compared to 8.1 mg/L in March and 5.5 mg/L in October.

Fish movement rates appeared to be associated with both water temperature and dissolved oxygen. Movement increased from 0.22 km/day in March to 0.65 km/day in June, then steadily declined to only 0.01 km/day in October (Figure 3).

Water temperatures remained high during August and early September when fish movements were declining. In contrast, DO concentrations steadily declined during summer (Figure 4). The longest distance moved in 1 day by a fish was 3.56 km, while the overall average was 0.29 km/day (SE = 0.04, F month = 3.06, $p \leq 0.003$).

No studies to date have quantified the different proportions of habitat and aquatic vegetation types in upper Lake Marion. Over the course of the study, 36 percent of fish locations were habitats composed of open water with scattered cypress trees and depths of 2 to 3 m (Figure 5). Creek channels did not run through these locations. For 30 percent of the time, grass carp locations were in shallow flats 1 to 2 m deep. Fish were located in thick cypress swamps or open-water areas with creek channels 19 and 15 percent of the time, respectively.

Fish were congregated in either open-water shallow flats or thick cypress swamps during the months February through April (Table 1). Numbers of fish in the cypress swamps decreased during May, and the number of fish in open-water cypress stands increased. No fish were located in the cypress swamp by June, and few fish were located in the open-water creek channel habitats. Most were either in the open-water shallow flats or open-water cypress stands. Fish remained in the open-water creek channel or the open-water cypress stands exclusively during July through October.

Almost 72 percent of recorded grass carp locations were in areas with aquatic vegetation at the water's surface. More specifically, 18 percent of the locations were areas with vegetation that covered ≥50 percent of the surface and 54 percent in areas with vegetation that covered <50 percent of the surface (Figure 6). Areas with submersed vegetation accounted for 25 percent of fish locations, and only 3 percent of the locations were areas with sparse aquatic vegetation.

On a seasonal basis, grass carp locations demonstrated a trend opposite that of the progressive increase in aquatic plant biomass. Whereas the summer is characterized by

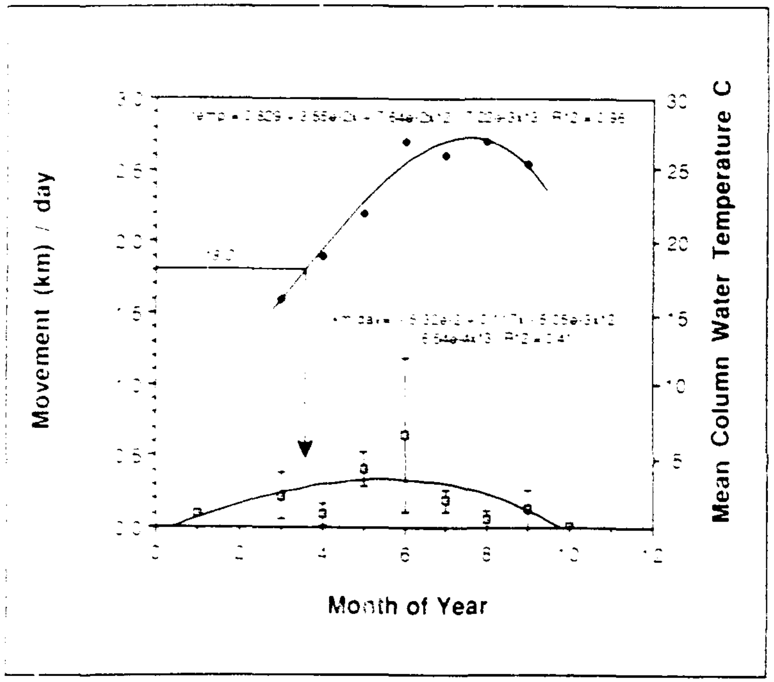


Figure 3. Average daily movement and water temperatures at locations of radio-tagged adult triploid grass carp in upper Lake Marion by month, 1989-1990. Vertical bars represent ±2 standard error

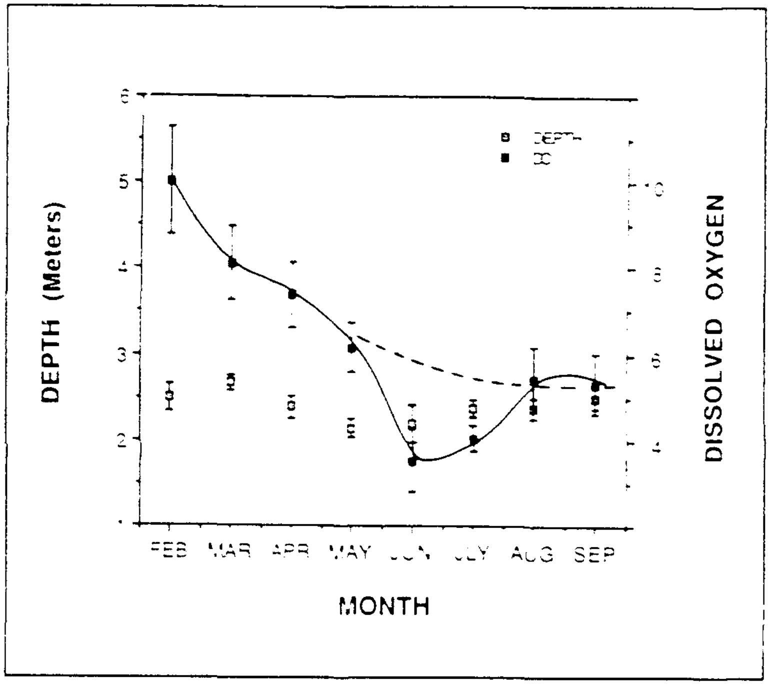


Figure 4. Average depth and dissolved oxygen at locations occupied by adult radio-tagged triploid grass carp in upper Lake Marion, 1989-1990. Vertical bars represent ±2 standard error

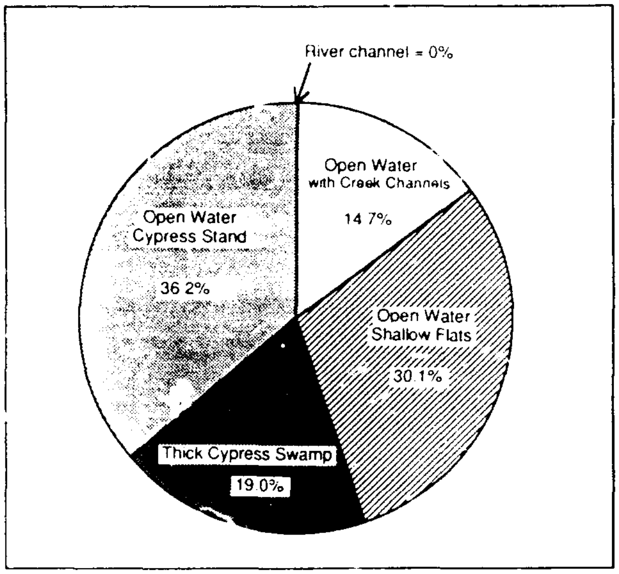


Figure 5. Habitat utilization by radio-tagged adult triploid grass carp in upper Lake Marion, 1989-1990

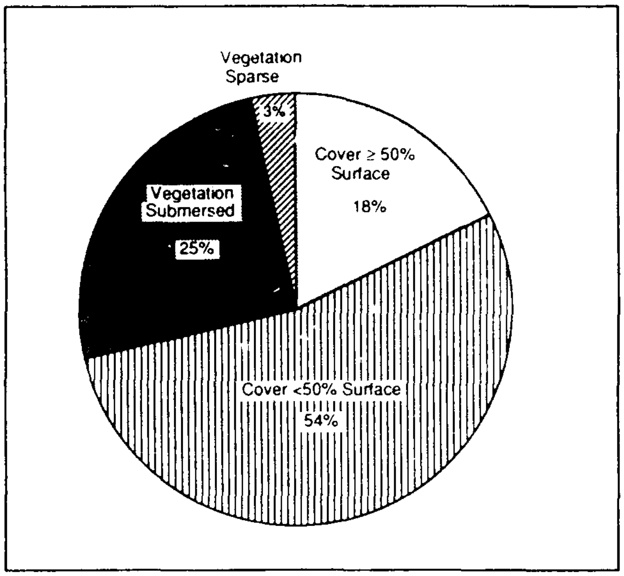


Figure 6. Aquatic vegetation densities of locations used by radio-tagged adult triploid grass carp in upper Lake Marion, 1989-1990

Table 1
Percentage of Grass Carp Locations in Relation to Habitat Categories in Lake Marion, SC, 1989-1990

Month	Habitat Category,[1] percent				
	RC	OWCC	OWSF	TCS	OWCS
February	0	0	33	67	0
March	0	0	24	76	0
April	0	0	36	64	0
May	0	[illegible]	79	6	15
June	0	6	47	0	47
July	0	23	0	0	77
August	0	41	0	0	59
September	0	36	0	0	64
October	0	50	0	0	50

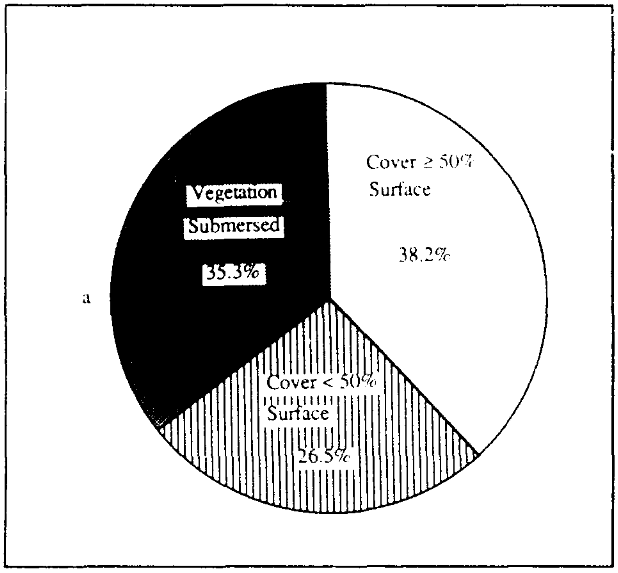
[1] RC - river channel, OWCC - open water with creek channels, OWSF - open-water shallow flats, TCS - thick cypress swamps, and OWCS - open water cypress stands.

dense aquatic vegetation stands that reach the water surface, more grass carp were located in slightly deeper areas where <50 percent of the surface showed aquatic vegetation. The springtime frequency of observations for vegetated areas with ≥50 percent surface coverage, <50 surface coverage, submersed, and sparse vegetation was 38, 27, 35 and 0 percent, respectively (Figure 7a). The summer frequency of observations was 12, 62, 22, and 4 percent, respectively (Figure 7b).

Over the course of the study, 66 percent of fish locations were in areas dominated by *Hydrilla* (Figure 8). *Egeria densa* and *Chara* were predominant vegetation types in only 11 and 3 percent of fish locations. Other vegetation types that included duckweed, *Nitella*, and coontail accounted for 20 percent of the locations, but no single species exceeded 2 percent.

Discussion

Downlake-directed movement during spring and early summer was probably in response to low DO levels that historically occur in the upper part of the lake. Oxygen levels in the swamp above the lake and in the upper portion of the lake itself decline to as low as 0.1 mg/L (Bates and Marcus 1989), a condition that is lethal to grass carp (Yeh 1959). Prolonged exposure to sublethal low DO concentrations could reduce consumption of aquatic plants by grass carp. According to Prowse (1971), a decrease in the oxygen content lowers metabolic rate.



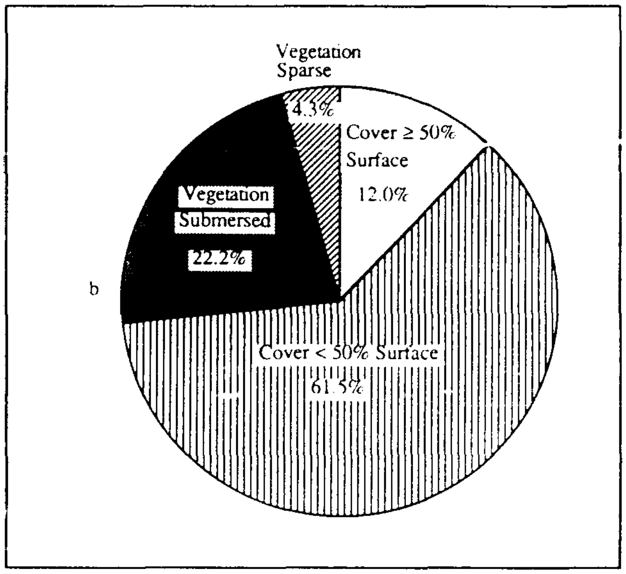


Figure 7. Aquatic vegetation densities during the spring (a) and summer (b) at locations used by radio-tagged adult triploid grass carp in upper Lake Marion, 1989-1990

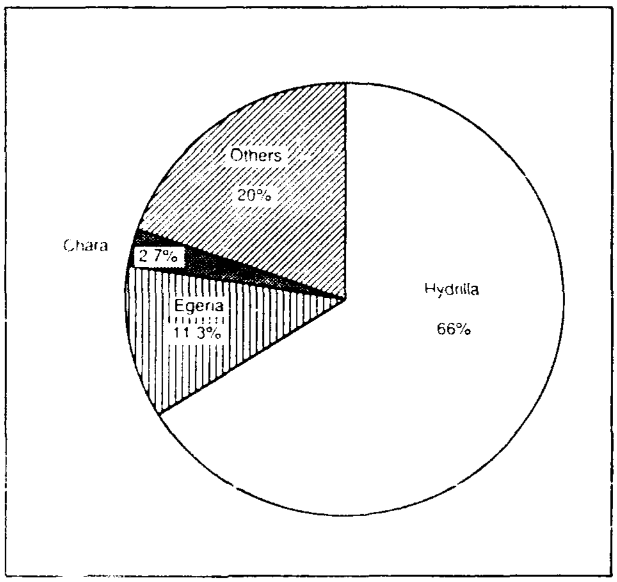


Figure 8. Predominant aquatic vegetation at locations used by radio-tagged adult triploid grass carp in upper Lake Marion, 1989-1990

Therefore, grass carp may consume less aquatic vegetation and reduce their daily movements at low oxygen levels.

Water temperatures could influence grass carp movement in two ways: by inducing spawning behavior and by an increased metabolic rate and food consumption rate at warmer water temperatures. Opuszynski (1972) determined that daily food consumption was 50 percent of body weight until water temperature reached 20° C; then, daily consumption increased to 100 to 120 percent body weight at 22° C. Lower water temperatures were reported to decrease rapidity of movement, whereas warmer water temperatures caused increased rapidity in grass carp movement (Nixon and Miller 1978).

In the present study, grass carp daily movement increased dramatically as water temperatures reached 15° to 17° C, the temperature range that reportedly initiates mass movements to spawning areas (Aliev 1976, Nezdolii and Mitrofanov 1975). However, the direction of grass carp movement was exactly opposite the upstream direction. This downlake movement was probably in response to declining DO concentrations in the upper lake.

Magnitude of movement was comparable to that reported for adult fish by Bain et al. (1990). They reported that adult fish movement averaged 33 km over a 4-month period (i.e., about 0.27 km/day) and that one fish traveled 6 km/day. It is difficult to make direct comparisons between studies without

knowledge of the frequency of observation. For example, a fish could travel 1 km each day for 10 successive days, but if it finished at its origin and had not been observed for 10 days, net daily movement would compute as zero.

Redistribution of grass carp from open-water shallow flats and thick cypress swamps to open-water creek channel and open-water cypress stands, both of which are downlake areas, was probably due to low DO in the upper lake during the summer. Shallow flats where aquatic vegetation covers more than 50 percent of the surface are also characterized by low summer DO concentrations (Bates and Marcus 1989). Utilization of slightly deeper and slightly less vegetated areas probably provides grass carp with a suitable combination of food density and DO concentrations.

Locations predominated by *Hydrilla* constituted the majority of grass carp locations. *Hydrilla* is an excellent food for grass carp due to the soft nature of the plant and its high ash content (Tan 1970, Rottman 1977). Grass carp used in this study were large (626 mm total length) and, according to Sutton and Vandiver (1986), *Hydrilla* would be their preferred food. No data exist concerning the percentage of Lake Marion's total nuisance aquatic plants that the individual species comprise. Thus, no preferences for *Hydrilla* can be inferred in the present study. However, triploid grass carp remained in the upper part of Lake Marion, and these fish did not leave areas targeted for aquatic vegetation control. No long-distance migrations were observed, and fish showed no affinity for the Santee River channel.

Dissolved oxygen and temperature levels appeared to play an important part in the location and movement of fish. Telemetry data are needed during the fall-winter-spring transition. In addition, data on water quality and aquatic vegetation distribution for upper Lake Marion are needed to interpret movements relative to available habitat.

References

Aliev, D. S. 1976. The role of phytophagous fishes in the reconstruction of commercial fish fauna and the biological improvement of water. *Journal of Ichthyology* 16:229.

Bain, M. B., Webb, D. H., Tangedal, M. D., and Mangum, L. N. 1990. Movements and habitat use by grass carp in a large mainstream reservoir. *Transactions, American Fisheries Society* 119:553-561.

Bates, R. D., and Marcus, J. M. 1989. Hydrologic modification and its effect on wetland function in the Santee Swamp, South Carolina. South Carolina Dept. of Health and Environmental Control, Columbia, SC.

Beach, M. L., Miley, W. W., Van Dyke, J. M., and D. M. Riley. 1976. The effect of the Chinese grass carp (*Ctenopharyngodon idella* (Val.)) on the ecology of four Florida lakes, and its use for aquatic weed control. Report No. DNR-16. Florida Department of Natural Resources, Tallahassee, FL.

Inabinette, J. R. 1985. Water quality characteristics of Santee-Cooper lake systems. Santee Cooper Public Utility District, Moncks Corner, SC.

Miley, W. W., Leslie, A. J., Jr., and Van Dyke, J. M. 1979. The effects of grass carp (*Ctenopharyngodon idella* Val.) on vegetation and water quality in three central Florida lakes. Report No. DNR-22. Florida Department of Natural Resources, Tallahassee, FL.

Nezdolii, V. K., and Mitrofanov, V. P. 1975. Natural reproduction of the grass carp, *Ctenopharyngodon idella*, in the Ila River. *Journal of Ichthyology* 15:927-933.

Nixon, D. E., and Miller, R. L. 1978. Movements of grass carp, *Ctenopharyngodon*

idella, in an open reservoir system as determined by underwater telemetry. *Transactions, American Fisheries Society* 107:146-148.

Opuszynski, K. 1972. Use of phytophagous fish to control aquatic plants. *Aquaculture* (Netherlands) 1:61-74.

Pennwalt Corporation. 1984. Submersed aquatic weeds and algae guide. Philadelphia, PA.

Prowse, G. A. 1971. Experimental criteria for studying grass carp feeding in relation to weed control. *Progressive Fish-Culturist* 33:128-131.

Rottman, R. 1977. Management of weedy lakes and ponds with grass carp. *Bulletin, American Fisheries Society* 2:8-13.

Schramm, H. L., and Black, D. J. 1984. Anesthesia and surgical procedures for implanting radio transmitters into grass carp. *Progressive Fish-Culturist* 46:185-190.

South Carolina Aquatic Plant Management Council and South Carolina Water Resource Commission. 1989. South Carolina aquatic plant management plan. Columbia, SC.

Stanley, J. G., Miley, W. W., II, and Sutton, D. L. 1978. Reproductive requirements and likelihood for naturalization of escaped grass carp in the United States. *Transactions, American Fisheries Society* 107:119-128.

Sutton, D. L., and Vandiver, V. V., Jr. 1986. Grass carp: A fish for biological management of hydrilla and other aquatic weeds in Florida. Bulletin 867. Florida Agricultural Experiment Station, University of Florida, Gainesville.

Tan, Y. T. 1970. Composition and nutritive value of some grasses, plants and aquatic weeds tested as diets. *Journal of Fisheries Biology* 2:253-257.

Yeh, Y. T. 1959. A preliminary report on the oxygen consumption, energy requirements, asphyxiation point and respiratory quotient of fish fry and young fish. *Acta. Zool. Sin.* 11:117-137.

Progress During 1990 in the Search for Biological Control Agents in Temperate Asia

by
Joseph K. Balciunas[1]

Introduction

Eurasian watermilfoil (*Myriophyllum spicatum*), hereafter referred to as milfoil, is a serious aquatic weed in many parts of continental United States. Effective insect biological control agents are not presently available to control this weed.

Another submersed aquatic, hydrilla (*Hydrilla verticillata*), is the most important aquatic weed throughout the southern United States, and unfortunately, its range is still expanding northward, especially along the eastern seaboard. Insects from Australia and India show promise for controlling hydrilla in its southern range. However, additional insects are likely to be required to control hydrilla in its new, more northerly infestations.

The US Army Corps of Engineers has agreed to financially assist a USDA Agricultural Research Service (ARS) effort to locate and test insects in temperate Asia as possible control agents for milfoil and hydrilla. This research is presently based in the recently established Sino-American Biological Control Laboratory (SABCL) in Beijing. The SABCL is a cooperative effort between ARS and the Chinese Academy of Agricultural Sciences (CAAC). The facilities of SABCL are housed in a portion of the bottom floor of the four-story Biological Control Institute building at CAAC's campus in the western suburbs of Beijing.

In September 1989, a few months after the quelling of the Tiananmen Square uprising, I made the first project visit, lasting 5 weeks, to China.[2] This initial visit familiarized me with the facilities, personnel, and capabilities of SABCL, as well as the availability of collecting areas in the vicinity of Beijing. Examination of specimens of milfoil and hydrilla at the National Herbarium at Academia Sinicae and at provincial herbaria gave me a much better grasp of the distribution and phenology of these weeds in China.

Extensive field trips to various sites in Sichuan and Hunan provinces demonstrated the presence of a diverse array of insects that might be useful as control agents for hydrilla. The field trips also provided an opportunity to meet scientists who might assist us in maintaining a "remote" lab/collection facility at these provincial sites.

The promising agents found in these provinces and in Beijing included an aquatic weevil, two species of aquatic moths, two species of *Hydrellia* flies, tip-damaging Chironomidae midge larvae, and some caddisfly larvae. Thus, this initial 1989 survey, although extremely limited, showed great potential for continued research in China.

Purpose

The goals for the 1990 research in China were greatly expanded by the addition of

[1] US Department of Agriculture, Agricultural Research Service, Australian Biological Control Laboratory, Townsville, Australia.

[2] J. K. Balciunas. 1990. Biocontrol agents from temperate areas of Asia. Pages 25-33 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dr. Gary R. Buckingham to the project as a co-investigator and as a result of his willingness to assist in the fieldwork in China.

During 1990, our plans were to (1) provide training in Gainesville, FL, for our Chinese collaborators, (2) continue this training of our assistants during our visits to Beijing, (3) provide a "short-course" training in Beijing for the collaborating scientists from the remote provinces, and (4) visit the field sites in the vicinity of Beijing (many sites had been added since the 1989 visit).

Then, I would search for hydrilla and milfoil insects in the northeast province of Liaoning, and for milfoil insects in Inner Mongolia. Dr. Buckingham would return to the more promising sites in Liaoning and Inner Mongolia for additional collecting. I would review the progress at the "remote laboratory" in Hunan Province, established after my 1989 visit. Then, I would search for natural enemies of hydrilla in Guangdong Province, and Dr. Buckingham would search for hydrilla insects in Jiangsu Province.

After all the above had been accomplished, both of us would meet in China to review progress and plan the research for 1991.

Progress Report

In February 1990, Dr. Wang Ren, Director of the SABCL, and Mr. Wang Yuan, the assistant for our aquatic weed project at the SABCL, arrived in Gainesville. Dr. Buckingham had arranged for them to receive training at the ARS Quarantine Lab in the identification, collection, and propagation of aquatic plants. He also provided training, including short-courses by taxonomic experts, in the collection, identification, and rearing of aquatic herbivorous insects. Staff from the ARS Lab in Fort Lauderdale, and from the Waterways Experiment Station biocontrol group, also availed themselves of the opportunity for training at these taxonomic short-courses.

Dr. Ren and Mr. Yuan also received several days of training at the ARS Fort Lauderdale lab in field release, establishment, and monitoring techniques. Dr. Ren returned to Beijing after 5 weeks, while Mr. Yuan continued his training until the end of May.

I arrived in Beijing, from Australia via Hong Kong, on 7 July 1990. My first few weeks in China were spent collecting in the northern provinces of Liaoning and Inner Mongolia. Mr. Yuan accompanied me to Shenyang, the capital of Liaoning Province and China's fourth largest city, from where we conducted our field investigations. During this time in Shenyang (9-15 July), we were assisted and escorted by Associate Professor Guan Guang-Qing, a botanist from Shenyang Agricultural University, which served as our base. Although Professor Guan did not speak English, he knew the names, frequently even the Latin names, of the dozens of aquatic plants we saw. He was friendly, enthusiastic, and helpful. We believe he will make a good collaborator for our Shenyang remote site, especially after he receives training in Beijing.

Hydrilla was present at most of the aquatic sites we visited, and was sometimes very abundant. The profusion of hydrilla in such a cold location (where water bodies freeze over by the end of November) indicates that hydrilla will most likely continue to spread northward in the United States. At one small pond our hydrilla sample yielded a dozen adult weevils, but they did not appear to be members of the genus *Bagous* (they are probably *Tanysphyrus*).

Blacklighting at this site the next evening produced an additional half dozen of these weevils. These *Tansphyrus* weevils refused to feed on any of the hydrilla portions we provided them, so we carried them back to Beijing for further testing. According to Professor Guan, *M. spicatum* is present in the vicinity of Shenyang, but we did not find any during this visit, although we did collect *M. verticillatum*.

After returning to Beijing and dropping off our samples, I flew to Hohhot, the capital of Inner Mongolia, with Dr. Ren. Assistant Professor Cao Rui, a botanist from Inner Mongolia University (and a personal friend of Dr. Ren), served as our guide during the 6 days (17-22 July) that we spent in Hohhot. Inner Mongolia lies on a high plateau, 1,000 m above sea level, and has an arid (less than 150 mm rain annually) and cold climate. The few permanent bodies of water there freeze before the end of October, but they frequently contain milfoil.

We collected at Ha Su Lake, a large reservoir approximately 50 km west of Hohhot; at Dai Lake, a very large natural lake 100 km southeast; and at Ba Bai Lake, a small reservoir on the southern fringe of Hohhot. We found a weevil, probably *Phytobius* sp. (previously, some species in this genus were called *Litodactylus*) attacking the milfoil. Adults of this weevil were especially common at Ba Bai Lake, where on our second visit Dr. Ren and I collected almost 50 individuals found on the surface of the water or crawling on the milfoil just beneath the water's surface. Unfortunately, our blacklight broke, and we could not collect these weevils by this usually productive method.

We returned to Beijing, not only with the live *Phytobius* we had collected, but also with bags of milfoil from each of the Inner Mongolia sites. These samples were processed in Berlese funnels at SABCL, and produced more adult weevils and more than 100 *Phytobius* larvae. Our hand-searches and sun-dry samples had yielded only five larvae in Hohhot. This was not surprising, since while these larvae will feed externally on milfoil leaves, they seem to prefer to burrow within milfoil stems.

During my week in Beijing (22-28 July), I continued the training of our project assistant, Mr. Yuan, which I had begun during my 1989 visit and Dr. Buckingham had continued in Gainesville. Another assistant, Mrs. Jiang Hua, had joined our project within the last few months. Mrs. Hua works for another institute in Beijing (the Institute for Plant Protection, Beijing Academy of Agricultural and Forestry Science) but has volunteered (and has been approved) to work on our biocontrol of aquatic weeds project. She is very cheerful, enthusiastic, and industrious, and also has a reasonable grasp of spoken English. Her addition to the project has greatly firmed the quality of research conducted at SABCL, especially during the absence of US scientists.

Before departing Beijing, for the benefit of Mr. Yuan, Mrs. Hua, and the collaborating scientists from the provinces, who would be receiving instruction in August in Beijing from Dr. Buckingham, I prepared six pages of written guidelines. These included techniques for collecting plants and herbivores, the procedures for rearing and preserving them, basic host-testing procedures, and (most importantly) the data that must be kept to accompany the above.

With Mrs. Hua's assistance, Mr. Yuan is now carrying out regular surveys of the hydrilla and milfoil sites near Beijing. Due to the upcoming Asian Games to be held in Beijing in September, the aquatic plants from most of the canals and ditches within the city had been manually removed. These operations included several of our more important canal sites. However, Mr. Yuan and Mrs. Hua located additional sites, mostly on the outskirts of Beijing. I managed to visit most of these sites—Chao Bai Jian River at Tong Xian, San Jia Dian Reservoir, Qiao Village Pond—and to revisit two sites from last year (Summer Palace Lake and August First Lake). Most of these Beijing sites contain hydrilla, but over half also have milfoil.

While processing our milfoil collection from August First Lake, we found *Phytobius* weevils, apparently the same species as we had collected in Inner Mongolia the previous week! On hydrilla, the leaf-mining *Hydrellia* spp. found last year had not yet reappeared, but a few of the stem-boring midges were already present.

After leaving extensive instructions with Mr. Yuan and Mrs. Hua on sampling strategy and procedures for keeping the *Phytobius* weevils and other insects alive until Dr. Buckingham arrives in late August, Dr. Ren and I flew to Huanan in central China.

The purpose of our 1-week (28 July-3 August) visit was to review the progress made by our remote site collaborator, Associate Professor Li Hongke, from the Hunan Academy of Agriculture in Changsha, the capital of Hunan Province. During my visit to Dong Ting Lake in Hunan Province in 1989, I had collected one specimen each of two species of *Bagous* weevils that fed on hydrilla. Professor Hongke had agreed to follow up on these promising results.

The next morning we departed Changsha for Yue Yang, located on the southeastern shore of Dong Ting Lake. Because of the old vehicle and the poor road, the 150-km trip required over 6 hours! We met with Dong Ting Lake Management Bureau (DTLMB) personnel that evening; the next morning we drove north to Lin Xiang County, which borders Hubei Province. There, at Chang An River Canal, we were finally able to collect a deeply submersed sample of hydrilla. The only herbivores we found in hand-searching this sample were a *Parapoynx* pupa and some caddisfly larvae. Previously, Professor Hongke's student assistant had collected some chrysomelid-like beetles on the hydrilla at that site.

The next day we drove to Lao Gang, where one of DTLMB's reed farms is located. The Director of Lao Gang Reed Farm, Mr. Yan Jianyong, had collected 10 weevils from hydrilla in two small ponds near the reed farm. One of these, Zhang's Pond, was the site where I had found the two *Bagous* weevils last year. We collected and processed hydrilla samples from both ponds. Two weevils were found, but they definitely were not a *Bagous* sp. (probably were *Notaris* sp.).

Later, I set these weevils up in my hotel room with a variety of aquatic plants. They ignored hydrilla but fed readily on water chestnut, *Trapa* sp. Mr. Jianyong returned with us to DTLMB's main office in Yue Yang, where he showed us the weevil specimens he had previously collected. Most were *Notaris*, but one, reared from a larvae burrowing in hydrilla, was a *Bagous*.

The next day we made the long trip back to Changsha, where Professor Hongke showed us four sites at which he had collected hydrilla herbivores. Only one of these now had hydrilla, which we collected and processed; however, we recovered no herbivores. The following morning, we went to Professor Hongke's laboratory to examine the various aquatic weed herbivores he and his assistant had collected. The chrysomelid beetles they had been trying to rear in a hydrilla-filled jar could not be found. Also, all the insect specimens from the various sites and hosts had been preserved in the same bottle of formalin.

I spent several hours explaining, with Dr. Ren translating, how to preserve and label insects, and the strategy and techniques to be used in collecting and testing aquatic herbivores. We now feel that Professor Hongke understands what must be done, and we are optimistic that next year's collecting at our Hunan "remote site" will be more productive.

On the weekend of 3 August, Dr. Ren and I flew to Guangzhou, the capital of the southern province of Guangdong. Guangzhou, formerly known as Canton, has recently been permitted special capitalistic freedoms by China's central communist government in order to attract capital investment from nearby Hong Kong. As a result, the city is becoming a "young" Hong Kong. Unlike most of China's cities and towns, which tend to be gray, drab, and dull, Guangzhou is active and bustling. New skyscrapers are going up, and motorcycles (and even private cars) are common.

We spent several days, assisted by staff from the Guangdong Academy of Agricultural Sciences, looking for hydrilla and its herbivores. While I had seen numerous herbarium specimens of hydrilla from Guangdong, we

were unable to find any that weekend. Apparently, the demand for seafood in Hong Kong has resulted in most land and canals being converted into aquaculture. These intensively managed aquatic systems do not support hydrilla. On 6 August, I left Guangzhou, via hydrofoil ferry to Hong Kong, to return to Australia.

Dr. Buckingham arrived in Beijing on 28 August. He monitored the progress made by our Chinese assistants in maintaining the insects I had left to be reared at SABCL, and visited the sites in and around Beijing until 10 September, when he and Mr. Yuan flew to Shenyang. While there, they collected with Professor Guan, and this time were also able to collect from *M. spicatum*. While in Shenyang, they determined that the *Tanysphyrus* weevil, which I had collected there earlier, fed on *Monochoria* sp. and not on hydrilla.

On 15 September, Dr. Buckingham flew to Hohhot and joined with Dr. Ren. Accompanied by Assistant Professor Rui and Mr. Li Yao from Inner Mongolia University, he revisited all three of my collection sites there. The weevil *Phytobius* was still attacking milfoil at all three sites, but no additional herbivores were found.

Back at the SABCL, from 20 to 22 September, Dr. Buckingham presented a short-course on collection, identification, and rearing of aquatic herbivores. Professor Guan, Assistant Professor Cao Rui, Mr. Yao, Mr. Yuan, and Mrs. Hua attended. On 23 September, Drs. Buckingham and Ren flew to Yangzhou, in Jiangsu Province. Accompanied by Professor Lin Gunlun and Professor Lu Ziqiang, Dean of Plant Protection, Jiangsu Agricultural College, they surveyed the local lakes. *Hydrellia* flies and tip-boring midges were common on the hydrilla there. On 26 September, Dr. Buckingham flew to Guangzhou.

At the end of September, I returned to Guangzhou from Australia, and met with Drs. Buckingham and Ren. We spent several days reviewing the accomplishments of 1990 and planning the research for 1991. Dr. Buckingham left to return to Florida on 29 September, hand-carrying *Hydrellia* from Beijing and Yangzhou. Small colonies were successfully established from these flies at the Gainesville quarantine facility. On 30 September, I left for Australia, where I prepared a written plan for the 1991 research.

Conclusions

The project to find biological control agents for hydrilla and milfoil in China was very productive during 1990. Our primary assistants received training in Florida and China. In addition, our collaborators from Liaoning and Inner Mongolia Provinces received training in Beijing. Besides the above provinces, we also searched for possible biological control agents in Hunan, Guangdong, and Jiangsu Provinces and established regular sampling sites in Beijing. Numerous aquatic herbivores were found (see Table 1). Several species of *Hydrellia* that attack hydrilla were exported to Gainesville quarantine. A plan for the research and fieldwork in China during 1991 was prepared and approved.

Table 1
Insects Found Attacking Aquatic Plants In China During 1990

Host Taxa	Insect Taxa	Feeding Damage	Sites Found
Haloragaceae *Myriophyllum spicatum* (Milfoil)	Coleoptera Curculionidae *Phytobius* sp.	Stem borer, flower and seed feeder	Beijing, Hohhot
	Diptera Chironomidae sp. 1	Tip midge	Hohhot
	sp. 2	Stem inhabitors	Beijing, Shenyang, Hohhot
	Hemiptera Aphididae	Sap sucker	Beijing, Hohhot
	Lepidoptera Pyralidae *Parapoynx* sp.	Leaf feeder	Beijing
Hydrocharitaceae *Hydrilla verticillata* (Water thyme)	Coleoptera Curculionidae *Bagous* spp.	Stem miner	Dong Ting Lake
	Donaciinae	Root grub	Linxiang Co.
	Diptera Chironomidae sp. 2	Tip midge	Beijing, Shenyang, Yangzhou
	sp. 2	Stem inhabitors	Most sites
	Ephydridae *Hydrellia prob. pakistanae*	Leaf miner	Most sites
	Hydrellia sp. b	Leaf miner	Most sites
	Hydrellia sp. c?	Stem miner	Yangzhou
	Lepidoptera Pyralidae *Parapoynx* sp.	Leaf feeder	Beijing, ChangSha, Shenyang, Yangzhou
Menyanthaceae *Nymphoides* sp. (Marsh wort)	Coleoptera Curculionidae *Bagous* spp.	Leaf-feeding adult	Hohhot
Pontederiaceae *Monochoria*	Coleoptera Curculionidae *Tanysphyrus*	Crown and stem borer	Liaoning
Potamogetonaceae *Potamogeton* (Pondweed)	Diptera Ephydridae *Hydrellia* spp	Leaf miner	Beijing
	Lepidoptera Pyralidae *Parapoynx* sp.	Leaf feeder	Beijing
Trapaceae *Trapa* (Water chestnut)	Coleoptera Chrysomelidae	Leaf feeder	Shenyang
	Curculionidae *Notaris*?	Leaf feeder	Dong Ting Lake

Quarantine Research for Hydrilla Control

by
Gary R. Buckingham[1]

Introduction

During 1990 the hydrilla quarantine research project hosted two Chinese visitors from the Sino-American Biological Control Laboratory, Beijing, for training in techniques used to study aquatic insect herbivores. African midges that attack hydrilla were received from cooperators, and an attempt was made to colonize them in quarantine. Colonies of an Australian hydrilla stem-boring weevil are being maintained in quarantine while awaiting permission for release. New germplasm of a hydrilla leaf-mining fly was obtained from Pakistan and from India and was released to cooperators. Two species of hydrilla leaf-mining flies were collected in northern China, carried to quarantine, and colonized. These will be evaluated for use in temperate climates of the United States. The quarantine research project continues to keep the "pipeline" open for introduction of new biocontrol agents.

Training of Chinese Visitors

In February 1990, Dr. Wang Ren and Mr. Wang Yuan from the Sino-American Biological Control Laboratory came to our laboratory for 1.5 months and 3 months training, respectively. The major subjects covered were plant and insect identification and use of keys, insect herbivore life histories, insect-rearing techniques, field evaluation of biocontrol agents (with Dr. Ted Center), and biological studies with a native fly that mines leaves of frog-bit, *Limnobium spongia* (Bosc) Steud. (by Mr. Yuan).

One of the additional benefits of this training session were the close ties that the US biocontrol researchers initiated with Dr. Dick Deonier, Miami University, Oxford, Ohio. Dr. Deonier is the foremost taxonomist working with the important biocontrol flies *Hydrellia.* He presented a training seminar for our visitors in Gainesville, which was also attended by Ted Center, Alan Dray, and Willey Durden of Fort Lauderdale; Al Cofrancesco and Mike Grodowitz of the WES; and Ed Snoddy of the TVA.

Dr. Charles O'Brien, Florida A&M University, Tallahassee, the foremost taxonomist of aquatic weevils, spent an afternoon in the field with our Chinese visitors demonstrating collecting techniques and a day in his home-laboratory discussing taxonomic characters. Dr. O'Brien visited weevil taxonomists and museums in Japan, Australia, and New Zealand in autumn 1989 on an ARS/USDA grant to revise the weevil genus *Bagous* from the first two countries. He has also received an AID grant to revise the African *Bagous* during 1991 and 1992.

Recently, Dr. O'Brien described several new aquatic weevil genera and species from South America collected by him through an AID grant, and he is revising the Indian *Bagous* as his time permits. Dr. O'Brien's projects help our biocontrol programs by providing names for our biocontrol agents, and also by providing an information base for future projects against other nuisance aquatic plants.

African Tip Midge

In May and June 1990, Emmanuel Okrah, formerly in our laboratory but now in Kumasi, Ghana, and Dr. Richard Markham, formerly with the Commonwealth Institute of Biological Control (CIBC) in Kenya, but

---

[1] US Department of Agriculture, Agricultural Research Service, Biological Control Laboratory, Gainesville, FL.

now residing in Davis, CA, went to Burundi in central Africa to collect a midge that damages hydrilla tips in Lake Tanganyika. This mysterious midge (or midges) was first found during exploration in 1976 by Robert Pemberton (Pemberton 1980) on an ARS contract and was studied later by Dr. Markham (Markham 1986) on a contract through the CIBC with ARS and Dr. Center.

During neither of these previous projects had the causal midge been positively identified although it was tentatively identified as a *Polypedilum* from Dr. Pemberton's specimens. Fortunately, Dr. Markham planned to be in Africa on other business and volunteered to make another attempt (with Okrah's help) to collect the midge.

This project was stimulated greatly by recent efforts in British Columbia to use a native or adventive tip-eating midge for Eurasian watermilfoil control. Officials there have high hopes of manipulating the midge in the field if they can learn to rear it. Stimulating mating is a major hurdle for rearing midges. Some species mate in swarms near the tops of tall trees; some mate in sun spots among vegetation; some mate near the soil surface; etc.

Hydrilla is found alongshore in large, windswept Lake Tanganyika, which covers 13,000 square miles compared to about 1,200 square miles for Lake Okeechobee, Florida. Lake Tanganyika is larger than two of the Great Lakes. Okrah and Dr. Markham collected plants by snorkeling or by boat in areas with resident crocodiles. Apparently, they almost swam into a crocodile area, until they figured out why a man on shore was desperately yelling at them. Dr. Markham left after a week, and Okrah then hired local youngsters to help him.

The Lake Tanganyika hydrilla differs greatly from most of our Florida hydrilla. The roots are well developed and almost woody, apparently to provide an anchorage against waves. The plant is small, with small almost leathery leaves and very compact apical buds. Most of the buds were missing or fell from the plants during shipment. They fell off because midge larvae had tunneled into them and had eaten the insides. Not all damaged buds fell off, however; some remained, with new shoots growing from their bases. The tips of these new shoots were usually also attacked.

Larvae of two species of midges, both in the genus *Polypedilum*, were recovered from the damaged buds. Both species were found inside the plants, one species naked and the other in a silken tube. I believe that both species are herbivores; certainly, the naked species is. The British Columbia milfoil species lives in a silken tube, suggesting that our silken tube species may also be a herbivore, rather than merely an invader of the naked species' tunnel. Various other midge species lived in silken tubes on the outside of the plants, but those species undoubtedly fed on algae. Although most damage was along the upper stem and in the bud, holes were also eaten in many of the apical leaves.

Okrah examined 2,317 hydrilla stems; of these, 80 percent had no tip, 60 percent of the tips present were damaged, and 7 percent of the damaged tips had larvae. The extremely low numbers of larvae found in the buds during this and previous projects suggest that the larvae might be very sensitive to plant disturbance and might drop off the plant quickly. Although many buds had old damage, many had fresh damage without larvae. We were unable to solve the mating riddle for these species and thus rear them; however, we did confirm that the damage was caused by midges and obtained adults of both species.

Dr. John Epler, a consultant from Tallahassee, identified the midges and associated all stages with the adults. He believes that if they are someday introduced into Florida, the males will be distinguishable, but the females and larvae will be indistinguishable from Florida species. The adults of the two species differ from each other by the presence or absence of small hairs on the wings.

New Hydrilla Fly Germplasm

In August 1990 we finally obtained the hydrilla leaf-mining fly, *Hydrellia pakistanae* Deonier, from the CIBC station in Pakistan to increase our genetic base. The flies that were released previously in Florida were from India. The initial laboratory host-specificity tests with this species were conducted by the CIBC in Pakistan, and the field specificity data were obtained by them. After Dr. Deonier confirmed that the Pakistan flies were the same as our Indian flies, we sent larvae of the F3 generation to Ted Center and to Greg Jubinsky of the Florida Department of Natural Resources.

On my way to China this past summer, I stopped in India with the objective to collect hydrilla and milfoil insects in the mountains of Kashmir. I had discovered several potential agents during a trip in 1985. A secondary objective, however, if I were unable to visit Kashmir, was to collect *H. pakistanae* and the hydrilla tuber weevil, *Bagous affinis* Hustache, at Bangalore in southern India where our original colonies were collected.

Since I was not permitted to travel to Kashmir because of hostilities there, I went to Bangalore. In Bangalore I was aided by Dr. T. Sankaran and Mr. Krishnaswamy who has retired from the CIBC Indian Station. Traveling two directions from Bangalore, we found the waterways either dry or filled with muddy water from recent rain runoff. However, with 2 days remaining and traveling towards Mysore, we found ponds that had small amounts of hydrilla infested with flies.

My shipment to Gainesville was successful, and we released the F3 generation of these Indian *H. pakistanae* to Ted Center and Greg Jubinsky. We are uncertain if these early-generation flies are more fit than the flies reared for several years, but it is a general rule that the less laboratory rearing of biocontrol agents, the greater the chance of success.

I collected only one *B. affinis*, a female, which is still alive but has produced only infertile eggs. We also colonized a second species of hydrilla fly that was mentioned in a publication by Krishnaswamy and Chacko (1990) earlier this year. We had received that species in 1985 but were unable to colonize it.

Australian Stem Weevil

At last year's annual meeting, I reported submittal of the request for release of the Australian stem-boring weevil, *Bagous* n. sp. Z, to the Federal Technical Advisory Group (TAG). It has taken 1 year, but we have received permission from both the TAG and the Florida Arthropod and Pathogen Introduction Committee. The permit for release is now in the Animal and Plant Health Inspection Service, USDA, offices in Maryland, awaiting an evaluation by their Environmental Assessment Staff to determine if an Environmental Assessment is neccssary.

As most of you probably remember, adults of this weevil cut the hydrilla stems which contain the eggs and larvae. These stem fragments float to shore, where the larvae complete their development inside the stems. Pupation occurs in the layer of decaying plants or in the soil. We are continuing to rear this weevil in expectation of permission to release it.

China Flies

As Joe Balciunas has already mentioned, I visited China during September 1990 and carried back hydrilla infested with flies. The material was from three locations: Beijing; Shenyang, north of Beijing; and Yangzhou, south of Beijing near Shanghai. A total of four females and four males emerged from Beijing, and one female and one male emerged from Yangzhou. These 10 flies, including two species, were combined to ensure mating because we were unable to differentiate the live males.

In the F1 generation we obtained 33 females, 30 males of both species mixed, and have now obtained 56 mixed females in the F2 generation, which is still emerging. The flies from Shenyang did not emerge until a

month after arrival in the laboratory (2 months after collection), but we had greater numbers: 10 females and 19 males of both species mixed. The F1 generation is now emerging.

The two Chinese *Hydrellia* are very similar to the two Indian species and may eventually prove to be the same species. Females can be separated relatively easily by the shape of small hardened structures at the end of the abdomen, called cerci. The cerci of living *H. pakistanae* are lighter brown than those of the other species and are L-shaped rather than triangular. Facial reflection is golden in *H. pakistanae* females and silver in the other species. Dead males can be easily separated by their genitalia, but it is difficult to separate live males. Dr. Deonier is presently studying these species, and it is hoped that he will be able to sort out this complex.

Future Studies

During the next year we plan to conduct cross-mating studies with the Chinese and Indian flies; we also plan host-specificity studies with the silver-faced species and, if warranted, with the *H. pakistanae*-like species. If *H. pakistanae* is indeed in China, we will conduct tests with only a few key plant species just to ensure that its host range is the same as that of the Indian population. The climate of Shenyang is similar to that in Minnesota, so these Chinese flies should be able to establish in our northern hydrilla locations.

We hope to be able to release *Bagous* n. sp. Z to Dr. Center soon, but I have no idea when that might be. If Dr. Balciunas' and my foreign travel plans are approved, I will travel to western China during August 1991 with Dr. Wang Ren to survey on Eurasian watermilfoil.

References

Krishnaswamy, S., and Chacko, M. J. 1990. *Hydrellia* spp. [Diptera: Ephydridae] attacking *Hydrilla verticillata* in South India. *Entomophaga* 35:211-216.

Markham, R. H. 1986. Biological control agents of *Hydrilla verticillata*; Final report on surveys in East Africa, 1981-1984. Miscellaneous Paper A-86-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Pemberton, R. W. 1980. Exploration for natural enemies of *Hydrilla verticillata* in Eastern Africa. Miscellaneous Paper A-80-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The Future of Microbial Herbicides

by
James P. Stack[1]

Introduction

The future of microbial herbicides looks brighter today than at any time in the recent past. This optimistic outlook can be justified by recent technical advances and sociopolitical changes that make the climate for development and implementation of biological controls near ideal.

The conditions that make the climate ideal for microbial herbicides in general are applicable to microbial herbicides for aquatic environments, as well. The emphasis of this paper is on development of fungi as microbial herbicides for nuisance aquatic plants, though examples will pertain to the larger framework of microbial herbicides in any system.

The objective of this paper is not to predict the future, but rather to identify the potential that is yet to be realized in the area of microbial herbicide development. Where are we now and where might we be in 10 years based on our present potential?

Biological Control In Transition

The approach

The present approach to microbial herbicide development, and biocontrol in general, is in transition from biological control as a scientific curiosity to biocontrol as a management tool and commercial opportunity. This transition period has seen a change in methods of selecting microbial control agents from empirically driven selection systems to analytical selection systems. Performance criteria have been critically defined, and evaluations have changed from qualitative to quantitative. These changes in approach will optimize the selection process for agents with high probabilities of success for biological control in agricultural or natural ecosystems, i.e., the real world.

This transition in approach to microbial herbicide development is evident based on the fact that two mycoherbicides are commercially available in the United States (Bowers 1986, Kenney 1986); the experience gained in the commercialization of the first bioherbicide is being used to increase the efficiency of the development process (Hasan and Ayres 1990, Templeton 1986); and several mycoherbicide programs are at the field-testing stage of development (Charudattan 1991, Hasan 1988).

Starting assumptions

In the past, much of the effort to develop biological controls was dominated by the assumptions that (a) biologicals are a special case not subject to the same developmental constraints as synthetics, (b) the consumer will pay more for less efficacy if it is biological, and (c) the general public is anxiously awaiting biological controls.

Biologicals face many of the same constraints as the synthetic chemicals: cost-effectiveness, efficacy, shelf life, formulation, and environmental safety. The assumption that the consumer, whether farmer or lake manager, will accept a biological product that costs more and is less effective will not be borne out in the market place. Biological controls will be held to the same performance standards as competing products.

[1] EcoScience Laboratories, Inc., Amherst, MA.

A desire on the part of the general public to stop using synthetics should not be construed as an equal desire to start using biologicals. The public has become sensitized to exposure to things they cannot see. They need to understand biological control and biocontrol agents.

Management Philosophy

The two strategies for microbial herbicide development often stated in the literature are classical and mycoherbicide (Hasan and Ayres 1990, Templeton 1982). These strategies must be considered within the context of overall system management. We should consider not only whether the different management practices within any system are compatible, but also whether they can be made interactive to the benefit of the total system; that is, they should be not just compatible, but truly integrated controls.

Classical

With the classical strategy, the biocontrol agent becomes endemic after introduction. This strategy is appropriate for introduced species using pathogens from the same geographic source as the target species. There are many examples of classical biocontrol of terrestrial species of nuisance plants, which are under various stages of development (Charudattan 1991, Hasan 1988, Hasan and Ayres 1990).

The intended result from the classical approach is to have the agent population establish in the application year and increase in subsequent years (Quednau 1990). In theory, this strategy is ecosystem stabilizing and results in long-term control. The short-term objective is to regulate the target population rather than to eradicate it, with eradication perhaps being a long-term objective.

At present, the US Environmental Protection Agency (USEPA) requires data on persistence of microbials applied to the environment. It is believed that microbes which persist present a greater environmental risk. Persistent microbes will require more environmental impact data, and thus will likely be more difficult to register. Hence, the current regulatory atmosphere appears less conducive to the development and application of microbial agents for classical biocontrol.

Mycoherbicide

This strategy requires application of the agent annually. The strategy is one of inundation and is appropriate for indigenous species of nuisance aquatic plants using pathogens from the indigenous target species population. As with classical control agents, there are many examples of mycoherbicide biocontrols of terrestrial nuisance species under various stages of development (Charudattan 1991, Hasan 1988, Hasan and Ayres 1990).

Most industrial programs are aimed at developing agents that fit in the mycoherbicide approach category, and these are likely to reach the marketplace first. That is not to suggest that classical biocontrol agents will not be developed and be successful; their development and commercialization may lag behind until sufficient data and experience with microbials demonstrate their safety.

The mycoherbicide approach is designed for within-season eradication (or substantial reduction) of a target plant population. Different systems in which control is to be effected may permit the selection of agents where control is dependent upon pathogen population increase (polycyclic disease cycle; rate of pathogen population increase drives epidemic) or independent of pathogen population increase (monocyclic disease cycle; amount of initial pathogen inoculum drives epidemic) within the application season. A pathogen capable of population increase subsequent to application may be applied at much lower rates, making control more cost effective. This is likely to be a focal point in the future.

Integrated controls - synthetics

During this transition period of biocontrol development, it might be more profitable to develop ways to utilize biologicals with the synthetic chemicals rather than instead of them. There have been successful attempts at combined biological/chemical controls of nuisance aquatic plants including Eurasian watermilfoil (Sorsa, Nordheim, and Andrews 1988) and waterhyacinth (Charudattan 1986). Many advantages to the implementation of combined biological/chemical controls have been noted, including the following:

- There is lowered risk to selection for resistance to the synthetic, since the two active ingredients operate by different mechanisms.

- The combined use of two control agents will result in the application of less of each of the active ingredients.

- The chemical can compensate for the lack of speed in the biological, and the combined action of the two agents can achieve the high level of efficacy required at concentrations of the synthetic of lesser environmental concern.

Resistance in target plant populations to microbial herbicides is also a possibility. The potential for combined applications to decrease the pressure for developing resistance needs investigation. How the strategy (classical versus inundative) of biocontrol implemented affects the probability of resistance arising in the target population has been discussed theoretically (Briese 1989).

Integrated controls - biologicals

Once the mechanisms of action for microbials are established, it is conceivable that microbes with different mechanisms could be combined to elicit a higher level of efficacy than either one could provide alone. This concept could also be applied to microbe-insect combinations, with the insect serving as an active ingredient as well as a delivery vehicle for the microbe. Preliminary reports of microbe-microbe and microbe-insect combinations have been reviewed (Hasan and Ayres 1990).

Integrated controls - cultural

There are perhaps more chances of integrating microbial and cultural practices in terrestrial systems than in aquatic systems. One possibility is the application of a microbial immediately following a mechanical harvesting operation. The wounds created by the harvesting may weaken the host and provide sites of entry for the pathogen. To my knowledge, this has not yet been attempted.

Technology: Vehicle to the Future

For most human endeavors, progress is a function of technology. With any technology there are many prerequisites to successful development and implementation. Both the attainment of success and the rate at which the success is attained often depend upon how we use existing technology to solve problems and generate new technology.

What technologies and applications are likely to impact the future of microbial herbicides? Molecular biology and computer technology (hardware and software) will have major impacts on the future of microbial herbicide development. Advances in these areas will lead to advances important to microbial herbicides, including:

- Understanding mechanisms of action.

- Predicting the behavior of populations of microorganisms.

- Monitoring the performance of microbial control agents.

- Developing efficient strain selection systems.

- Developing knowledge-based management programs.

Strain selection and improvement

Critical to the success of any microbial development system is strain selection and improvement. Most selection systems of the past could be described as empirical and random. The selection systems of the future will be sophisticated mechanism-driven systems. Microbial development will be target system-specific and task-oriented. What task must the agent accomplish, and what attributes must the agent have in order to accomplish that task? Selection and evaluation assays will be developed based on the necessary attributes. They will reflect the mechanism of action in the target system.

The efficiency of strain selection will be enhanced by the development of computer-aided selection. Expert systems will help determine the minimum traits necessary for consideration of a microbial control agent. Databases with potential agent profiles will identify which candidate agents to test for a given system. The agent profile will contain information on the key traits under consideration, e.g., lectin-mediated attachment and spore production in submerged fermentation. The profile will also provide information on whether key traits are subject to genetic or cultural manipulation, and whether variation exists in the natural population.

Designed agents

It is now possible to manipulate the genomes of bacteria, fungi, and yeasts. Recombinant DNA technology significantly improved the efficiency of manipulation over traditional mutagenesis. The regulatory agencies and the general public are becoming more informed of the technology and more comfortable with its application to problem solving.

Intelligent application of this technology will facilitate the development and utilization of agents designed for a specific task. This will, in turn, improve the efficacy of the agents and reduce the potential for negative nontarget effects after their introduction to natural habitats. Example types of manipulations possible with the bacteria and fungi that may be used for the development of microbial herbicides include modifications of pathogenicity determinants and virulence determinants.

Pathogenicity determinants. Several stages of communication between a plant and a microbe are involved in the determination of compatibility or incompatibility (Halvorsen and Stacey 1986). Some of these stages have been characterized physiologically, biochemically, and/or genetically and been shown amenable to manipulation.

- **Deletion of avirulence genes**. Research with plant pathogenic bacteria has demonstrated the potential for modifying microbial agents to avoid plant host defense responses. In many plant-microbe systems, the microbial genome houses genes for the production of molecules that elicit a defense response in the plant (Keen and Staskawicz 1988). In some systems these are termed avirulence genes. When the avirulence genes are deleted or inactivated (not expressed), pathogenesis results (Staskawicz, Dahlbeck, and Keen 1984). Hence, a microbial agent could be modified to avoid the host defense response by deleting the genes that encode the elicitors of that response.

- **Insertion of defense-avoidance genes.** In some plant-pathogen interactions, the pathogen genome encodes a gene or genes for the production of enzymes that detoxify plant defense molecules, e.g., phytoalexins (Darvill and Albersheim 1984; Van Etten, Mathews, and Mathews 1989). One example of how this might be used in the development of a microbial herbicide can be found in the *Fusarium*-pea system. Certain strains of *Fusarium oxysporum* f. sp. *pisi* produce the enzyme pisatin

demethylase, which detoxifies the pea phytoalexin pisatin. The virulence of strains that fail to produce this enzyme is much reduced.

The pisatin demethylase gene was transferred to a plant pathogenic fungus not normally pathogenic to pea. The transformed strain expressed the pisatin demethylase gene and was virulent on pea (Schafer et al. 1989). This demonstrated the potential to introduce genes into a pathogen that enables the pathogen to overcome host defense mechanisms and to either expand or specifically tailor its host range.

Virulence determinants. Once compatibility has been established, several host and pathogen factors regulate the dynamics of the ensuing interaction. Pathogen enzymes that depolymerize plant cell wall components can greatly affect the rate at which the plant tissues are decomposed (Wijesundera, Bailey, and Byrde 1984), and have been shown to be one of the differences between virulent and hypovirulent strains of a pathogenic fungus (Marcus et al. 1986). Two such enzyme systems, pectinases and cellulases, have been well characterized and shown amenable to manipulation in bacterial (Collmer et al. 1986) and fungal (Dean and Timberlake 1989) pathogens. Modification of the complement of enzymes or the regulation of synthesis could greatly improve the efficacy of microbial agents.

One aspect of microbial herbicide development important to both efficacy and safety is host range (Weidemann and Tebeest 1990). It may be desirable to alter the host range of microbial herbicides to make them either more or less specific. Several approaches are possible, including genetic manipulation of broad host range fungi to make their host range more restrictive. Success in this area has been achieved with the plant pathogenic fungus *Sclerotinia sclerotiorum* (Sands, Ford, and Miller 1990). This approach is worthy of more attention.

Formulation

One major obstacle to the application of biological control agents in general is the development of formulations that stabilize viability and maintain efficacy. This is especially true for aquatic environments, where the formulation should consider application parameters (e.g., sedimentation rate and trajectory) and plant interaction parameters (e.g., adhesiveness to the plant surface). Formulation of biologicals should be considered an integral part of their development, and not as an afterthought (Stack, Kenerley, and Pettit 1988).

Formulations of biologicals in the future will employ several tactics to enhance the performance of the agent. Potential examples include the amendment of formulations with chemicals that affect plant susceptibility (e.g., plant growth regulators, plant growth regulator inhibitors, low concentrations of herbicides, phytoalexin synthesis inhibitors), or with virulence enhancement compounds. Many pathogen-produced plant cell wall-degrading enzymes are subject to catabolite repression and are inducible. Designing a formulation that would prevent repression and provide an inducer might enhance virulence or the dynamics of disease progression.

Prospects for Market Entry

Regulatory atmosphere

All the technical advances made and to come will be underutilized in practice if the regulations governing microbial control agents preclude their widespread application. Based on recent developments, there is reason to be optimistic that the regulations will facilitate rather than impede the implementation of biological controls. Heightened concern over public health issues associated with the use of synthetic chemicals has resulted in a sense of urgency for the development of biological controls. In turn, a spirit of cooperation between industry and the regulatory agencies, primarily the USEPA, has evolved.

Evidence for the change in the regulatory process can be found in the frequency with which the USEPA solicits input from the major scientific societies, the involvement of leading scientists in developing guidelines, the constant refinement of the regulations, and the involvement of Congressional committees in the promotion of biological controls.

Education

One potential barrier not to be overlooked or taken lightly is the acceptance of biocontrol by users and the general public. It is incumbent upon scientists, regulatory agencies, and administrators to educate the public about the technology and the implications of its implementation.

A rational approach to development, an appropriate regulatory framework, and an educated public will enhance the probability of a speedy transition from laboratory-based biological control experimentation to the implementation of biological control as a management option.

References

Bowers, R. C. 1986. Commercialization of Collego - An industrialist's view. *Weed Science* 34(Suppl. 1):24-25.

Briese, D. T. 1989. Can microbial pesticides lick resistance? *Chemtech* (June):363-367.

Charudattan, R. 1986. Integrated control of water hyacinth (*Eichhornia crassipes*) with a pathogen, insects and herbicides. *Weed Science* 34 (Suppl. 1):26-30.

Charudattan, R. 1991. The mycoherbicide approach with plant pathogens. Pages 24-57 in *Microbial Control of Weeds*, David O. Tebeest, ed. Chapman and Hull, New York.

Collmer, A., Schoedel, C., Roeder, D. L., Ried, J. L., and Risler, J. F. 1986. Molecular cloning in *Escherichia coli* of *Erwinia chrysanthemi* genes encoding multiple forms of pectate lyase. *J. Bacteriol.* 161:913-920.

Darvill, A. G., and Albersheim, P. 1984. Phytoalexins and their elicitors - A defense against microbial infection in plants. *Ann. Rev. Plant Physiol.* 35:243-275.

Dean, R. A., and Timberlake, W. E. 1989. Regulation of the *Aspergillus nidulans* pectate lyase gene (pelA). *The Plant Cell* 1:275-284.

Halvorsen, L. J., and Stacey, G. 1986. Signal exchange in plant-microbe interactions. *Microbiological Reviews* 50:193-225.

Hasan, S. 1988. Biocontrol of weeds with microbes. Pages 129-151 in *Biocontrol of Plant Diseases,* K. G. Mukerji and K. L. Garg, eds. CRC Press, Boca Raton, FL.

Hasan, S., and Ayres, P. G. 1990. The control of weeds through fungi: Principles and prospects. *New Phytology* 115:201-222.

Keen, N. T., and Staskawicz, B. 1988. Host range determinants in plant pathogens and symbionts. *Ann. Rev. Microbiol.* 42:421-440.

Kenney, D. S. 1986. DeVine - the way it was developed - an industrialist's view. *Weed Science* 34 (Suppl. 1):15-16.

Marcus, L., Barash, I., Sneh, B., Koltin, Y., and Finkler, A. 1986. Purification and characterization of pectolytic enzymes produced by virulent and hypovirulent isolates of *Rhizoctonia solani* Kuhn. Physiol. Mol. Plant Pathol. 29:325-336.

Quednau, F. W. 1990. Introduction, permanent establishment, and dispersal in Eastern Canada of Olesicampe-Geniculatae Quednau and Lim (Hymenoptera, Ichneumonidae), an important biological control agent of the mountain ash sawfly, Pristiphora-Geniculata (Hartig) (Hymenoptera, Tenthredinidae). *Canadian Entomologist* 122:969-973.

Sands, D. C., Ford, E. J., and Miller, R. V. 1990. Genetic manipulation of broad host range fungi for biological control of weeds. *Weed Technol.* 4:471-474.

Schafer, W., Straney, D., Ciuffetti, L., Van Etten, H. D., and Yoder, O. C. 1989. One enzyme makes a fungal pathogen, but not a saprophyte, virulent on a new host plant. *Science* 246:247-249.

Sorsa, K. K., Nordheim, E. V., and Andrews, J. H. 1988. Integrated control of Eurasian water milfoil, *Myriophyllum spicatum*, by a fungal pathogen and a herbicide. *J. Aquat. Plant Manage.* 26:12-17.

Stack, J. P., Kenerley, C. M., and Pettit, R. 1988. Application of biological control agents. Pages 43-54 in *Biocontrol of Plant Diseases*, Vol II, K. G. Mukerji and K. L. Garg, eds. CRC Press, Boca Raton, FL.

Staskawicz, B. J., Dahlbeck, D., and Keen, N. T. 1984. Cloned avirulence gene of *Pseudomonas syringae* pv. *glycinae* determines race-specific incompatibility on *Glycine max* (L.) Merr. *Proc. Natl. Acad. Sci. USA* 81:6024-6028.

Templeton, George. 1982. Status of weed control with plant pathogens. Pages 29-44 in *Biological Control of Weeds with Plant Pathogens*, Charudattan and Walker, eds. John Wiley and Sons, New York.

Templeton, G. 1986. Mycoherbicide research at the University of Arkansas - past, present, and future. *Weed Science* 34 (Suppl. 1):35-37.

Van Etten, H. D., Mathews, D. E., and Mathews, P. S. 1989. *Ann. Rev. Phytopathol.* 27:143.

Weidemann, G. J., and Tebeest, D. O. 1990. Biology of host range testing for biocontrol of weeds. *Weed Technol.* 4:465-470.

Wijesundera, R. L. C., Bailey, J. A., and Byrde, R. J. W. 1984. Production of pectin lyase by *Colletotrichum lindemunthianum* in culture and in infected bean (*Phaseolus vulgaris*) tissue. *J. Gen. Microbiol.* 130:285-290.

The Potential for Biological Control of Eurasian Watermilfoil (*Myriophyllum spicatum*): Results of Brownington Pond, Vermont, Study and Multi-State Lake Survey

by

Robert P. Creed, Jr.,[1] *and Sallie P. Sheldon*[1]

Introduction

Eurasian watermilfoil (*Myriophyllum spicatum* L.) was accidentally introduced into North America sometime between the late 1800's and the 1940's (Bayley, Rabin, and Southwick 1968; Aiken, Newroth, and Wile 1979; Couch and Nelson 1986). Since its introduction, it has spread over much of North America (Aiken, Newroth, and Wile 1979; Couch and Nelson 1986; Nichols and Shaw 1986; Painter and McCabe 1988). It was first reported in Vermont in 1962 in Lake Champlain (personal communication, Holly Crosson, Vermont Agency of Natural Resources (VtANR)).

A number of methods, many of them quite costly, have been employed to control watermilfoil in Vermont and elsewhere, including use of drawdowns, herbicides, bottom barriers, and mechanical harvesting. In general, while these control methods may result in short-term reductions in watermilfoil abundance (Bayley, Rabin, and Southwick 1968; Nichols and Cottam 1972; Aiken, Newroth, and Wile 1979), they do not appear to have proven satisfactory for long-term control of this introduced nuisance aquatic plant (Bayley, Rabin, and Southwick 1968; Spencer and Lekic 1974; Aiken, Newroth, and Wile 1979).

Recently, attention has focused on the potential for biological control of *Myriophyllum spicatum*. Aquatic herbivores, such as the caterpillar *Acentria nivea* (=*Acentropus niveus*) (Lepidoptera; Pyralidae) and the weevil *Eurhychiopsis lecontei* (Coleoptera; Curculionidae), have been found associated with declining populations of watermilfoil in northeastern North America (Painter and McCabe 1988; Sheldon and Creed, personal observation), including Brownington Pond, Vermont. However, the exact role played by these herbivores in bringing about these declines remains undetermined.

We are currently evaluating the potential for *E. lecontei* and *A. nivea* to act as biological control agents for watermilfoil. There are two main objectives to this research. First, we are closely monitoring the fate of watermilfoil in Brownington Pond, which has recently displayed a watermilfoil decline (Figures 1 and 2). In addition to following the *M. spicatum* population in the pond, we are trying to determine the role herbivores may have in the northeastern United States.

The summer of 1990 was our first field season. During this season we determined the distribution and abundance of watermilfoil in Brownington Pond and conducted some experiments on the effects of weevil adults on *M. spicatum*. We also conducted a qualitative survey of watermilfoil and associated herbivores in several lakes in Vermont, New Hampshire, and Massachusetts. This paper highlights some of our major findings from last year. For more detailed discussions of this research, the reader is referred to our annual report.

[1] Department of Biology, Middlebury College, Middlebury, VT.

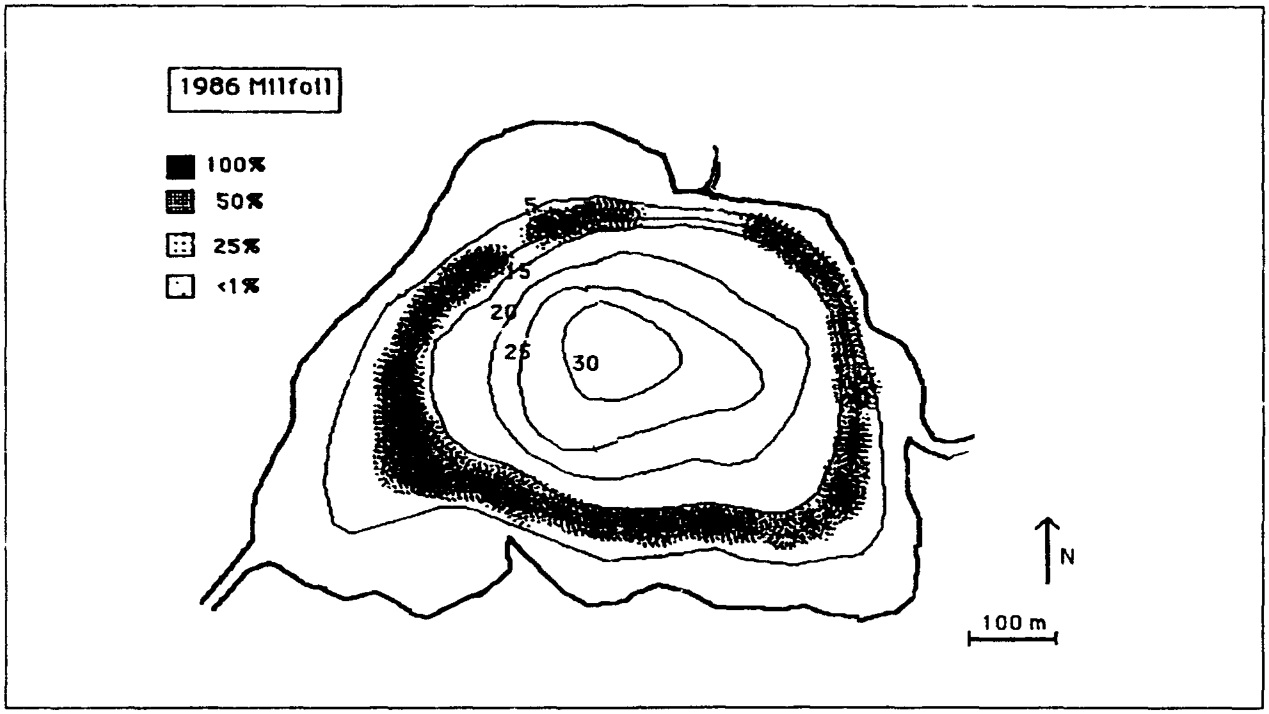


Figure 1. Distribution of M. spicatum in Brownington Pond in 1986. Most of the deeper littoral zone was covered by a dense bed of M. spicatum. (Data are from qualitative surveys conducted by the VtANR. Depth is in feet)

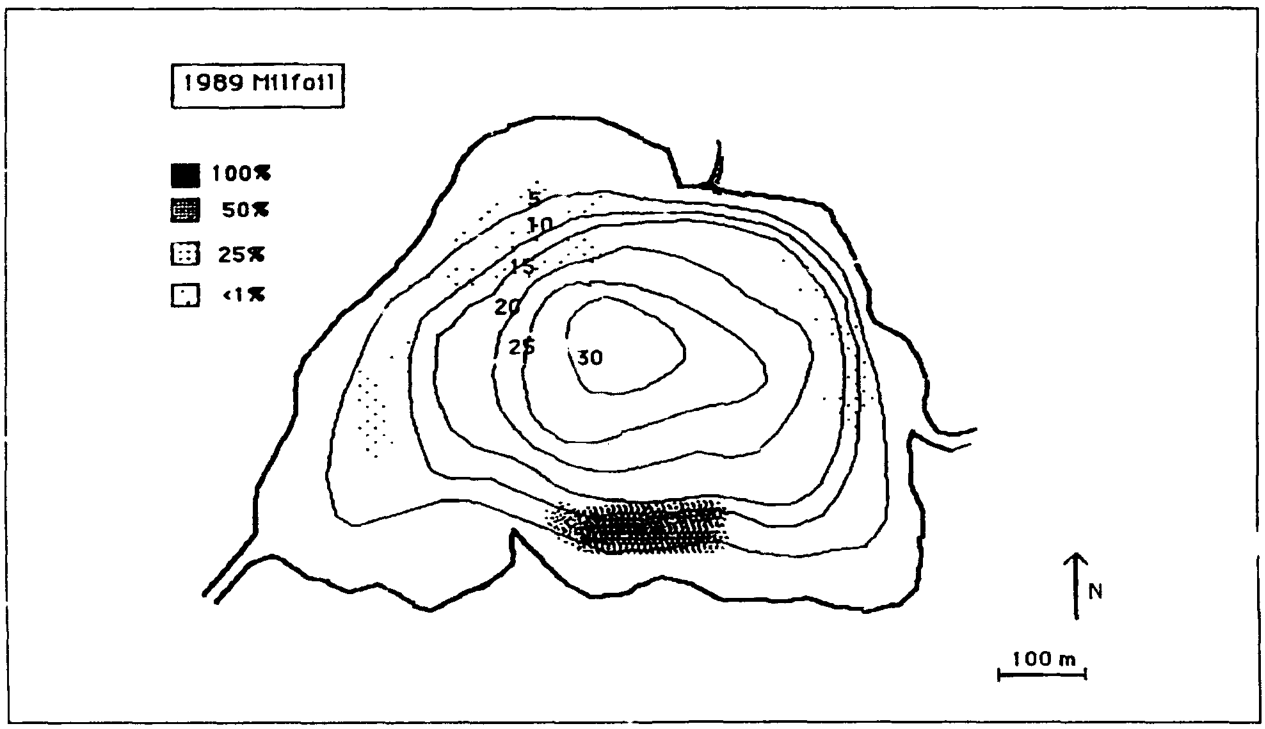


Figure 2. Distribution of M. spicatum in Brownington Pond in 1989, when there appeared to be only one bed of watermilfoil. (Data are from a qualitative survey conducted by S. Sheldon and D. Smith. Depth is in feet)

Brownington Pond

Materials and methods

We conducted a pond survey to determine the location of any watermilfoil beds in the littoral zone (two were found, see Figure 3). Then we began a program of sampling to monitor changes in *M. spicatum* density and biomass in the beds over time. Quadrat (0.25-m^2) samples were taken by a scuba diver approximately every 2 weeks, and three to six samples were taken per bed. Areas to be sampled were chosen haphazardly, although an attempt was made to collect samples from both the center and edges of the beds.

Upon completion of the littoral zone survey, we noticed that the two watermilfoil beds were located in water between 2.0 and 3.5 m deep. This absence of watermilfoil from shallower water seemed atypical, as *M. spicatum* is reported to take over much of the littoral zone up to a depth at which light is limited (Titus and Adams 1979). To better document this pattern, we sampled all macrophytes along transects perpendicular to shore on two dates, 17 July and 25 August 1990. As our primary goal was to describe the *M. spicatum* distribution pattern, the transects were run only in the vicinity of the two beds. Three transects were sampled per bed on each date by scuba divers.

We conducted three experiments to assess the effects of feeding by adult weevils on *M. spicatum* growth and the ability of weevils to remove leaf tissue from *M. spicatum* as well as a native milfoil, *Myriophyllum exalbescens* (*=sibiricum*).

Weevil tube experiment

The primary purpose of this experiment was to evaluate the effects of feeding by adult weevils on watermilfoil growth. The experimental chambers consisted of clear plastic tubes (42-mm inside diameter) set in a sediment-filled base made from PVC pipe, and were similar in design to those used by

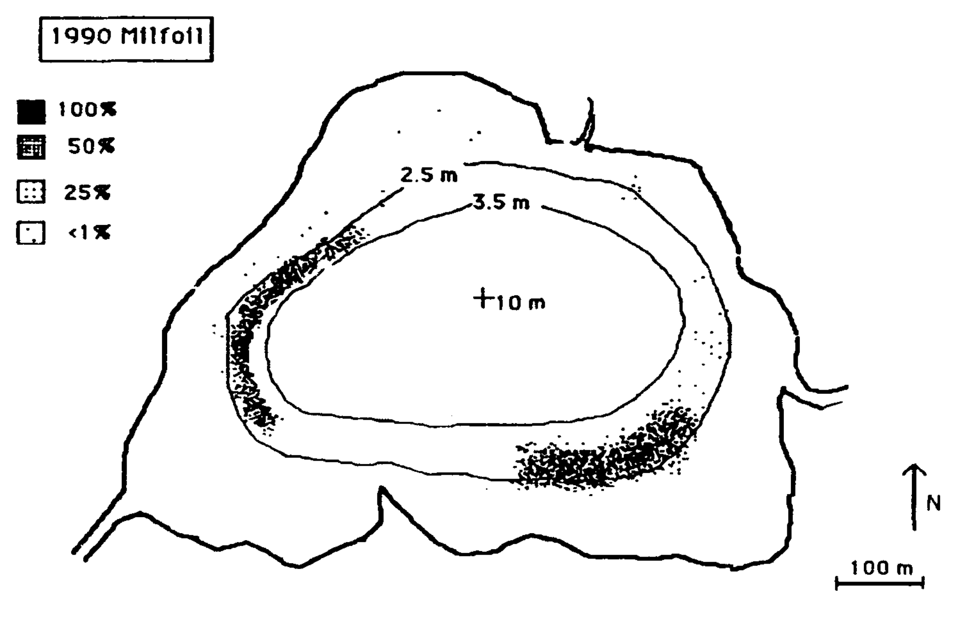


Figure 3. Distribution of M. spicatum in Brownington Pond in 1990. Watermilfoil abundance appears to have increased relative to 1989. Two distinct beds were present, referred to as West and South Beds. (Depth is in meters)

Barko and Smart (1980). Eighteen measured (length in millimeters) and preweighed (blotted wet weights in grams) apical fragments of *M. spicatum* (from which all visible invertebrates were removed) were then placed into individual chambers.

The chambers were placed in a 750-L outdoor wading pool. The experimental design was a randomized block design with three treatments (0, 2, and 4 adult weevils) per row, six replicates per treatment. Water temperatures ranged between 17 and 25 °C during the experiment, and the experiment was run for 13 days.

Weevil bag experiments I and II

Adult weevil feeding also results in the loss of considerable leaflet material and stem damage. To quantify these effects, we placed clean, intact *M. spicatum* stems (approximately 15 cm long) into pairs of plastic bags filled with pond water and weighted (to maintain a vertical position) with aquarium gravel. The bags were placed in the wading pool described above. Half of the bags received a single adult weevil (n = 5); the other five bags served as controls. Plants were removed from the bags after 5 days, and all loose leaflets and leaves remaining in the bag were removed and counted. The location of all stem bites was also recorded. Water temperatures during the experiment ranged from 17 to 25 °C.

A similar experiment was used to determine what effect adult weevils might have on a native milfoil when presented with both a native (*M. exalbescens*) and the exotic *M. spicatum*. The design of this experiment was identical to the one described above except that two stems were present in each bag, one of each milfoil species, n = 4. The experiment lasted for 8 days. Water temperatures ranged from 15 to 24 °C.

Results and discussion

Milfoil distribution and abundance The density of watermilfoil in the two beds ranged from roughly 100 to 200 stems per square meter over the summer. Stem density increased to a peak of about 200 stems/m^2 in both beds until mid-July and then declined to 100 to 130 stems/m^2 by August. In contrast to stem density, *M. spicatum* biomass displayed a steady increase from late June through August, from 20 to 150 g/m^2 in the South Bed and from 38 to 95 g/m^2 in the West Bed.

The transect data revealed that the watermilfoil beds were largely confined to depths between 2.0 and 3.5 m. There was a mix of native macrophytes and watermilfoil at the edges of the beds. However, there was little native macrophyte biomass in the center of the beds.

The data that were collected by the VtANR in 1986 and 1987 and that we collected in 1989 and 1990 demonstrate that a substantial decline has occurred in the Browningon Pond watermilfoil population. In 1986, watermilfoil ringed the deeper littoral zone of the pond. By 1989, only one bed remained. As of 1990, there were two beds in the pond, which suggests that the watermilfoil population may be rebounding. However, many *M. spicatum* plants exhibited herbivore damage from *Acentria* and *E. lecontei*, including lack of meristems.

In addition, no watermilfoil plants were observed flowering in 1990. Also, watermilfoil density was considerably lower than that observed in Lake Bomoseen, a Vermont lake that currently has a serious watermilfoil infestation. The native macrophytes, on the other hand, seemed quite healthy. *Potamogeton amplifolius* plants were very abundant and were observed flowering. *Heteranthera dubia* was also quite abundant, forming dense mats at the surface of the pond by late summer.

The absence of M. spicatum from shallow water is interesting, as this species often grows right up to the shoreline in many lakes. Crayfish (*Orconectes virilis*) are present in Brownington Pond and were most frequently encountered in shallow water. Recent work has shown that crayfish can have a strong

negative effect on macrophyte abundance in lakes (Abrahamsson 1966, Lodge and Lorman 1987, Coffey and Clayton 1988). We will conduct experiments next summer that will test the hypothesis that crayfish are causing this pattern of watermilfoil distribution in Brownington Pond. Alternative hypotheses include differences in sediment nutrients or particle size between deep and shallow water.

Weevil tube experiment. Feeding by adult weevils resulted in significant reductions in both the height of plants and final weight compared with controls (Figures 4a and 4b). Upon sampling the experiment, we found two larvae on two of the control plants. Mean change in length of the four control plants without larvae was 75 mm.

Larvae were also found in the weevil treatments (five of the two-weevil treatment replicates and four of the four-weevil treatment replicates). As larvae undoubtedly had some effect on watermilfoil growth, we reanalyzed the length, weight, and loss of leaves response data using ANCOVA, with number of larvae as the covariate. When the adult treatment effects are adjusted for the presence of larvae, adults were still found to have very significant effects on change in weight and loss of leaves (Table 1). Larvae had little or no effect on these variables. The effect of adults, however, on change in length was changed from being very significant ($p < 0.018$) to marginal significance ($p < 0.057$) when adjusted for presence of larvae (Table 1). The presence of larvae did contribute somewhat to reduction in length and weight, but their effect on weight was minor compared with that of the adults.

Leaves were lost from plants in all three treatments (Figure 4c). The loss of leaves in the control treatment was primarily the result of leaves dying at the point where the stems were planted in the sediment (Figure 5a). Plants from both of the weevil treatments lost the majority of leaves from the top due to weevil feeding (Figures 5b and 5c).

Weevil bag experiments I and II. In the first experiment, weevils removed a significant number of leaflets from watermilfoil stems but did not have a significant effect on whole leaf loss (Figures 6a and 6b). Four of the five weevils also fed on the stem, with most bites being near the top of the stem (Figure 7).

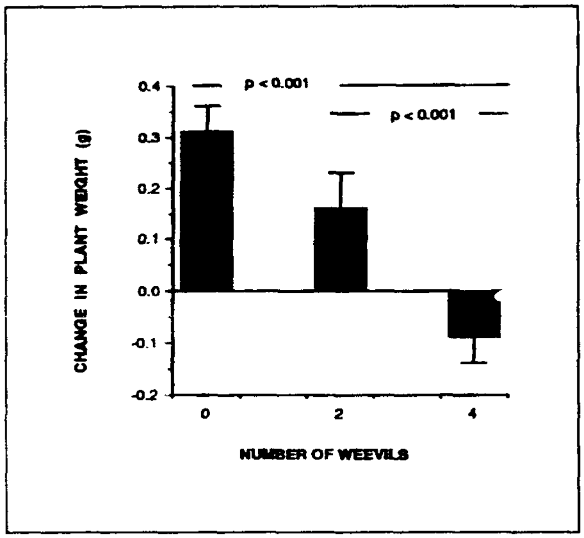
In the second experiment, when presented with two species of milfoil (*M. spicatum* and *M. exalbescens*), weevils still concentrated their feeding on *M. spicatum*. Weevils had no significant effect on *M. exalbescens* (Figures 8a and 8b), although they did remove a few leaflets. A total of 55 bites were found on *M. spicatum* stems, compared with only 6 found on the *M. exalbescens* stems (Figure 9). Again, the weevils concentrated their stem-feeding on the upper six internodes of the *M. spicatum* stems.

All three of these experiments produced promising results with respect to the potential for *E. lecontei* to serve as a biological control agent. Adult weevils were found to have significant negative effects on watermilfoil growth. Weevils were also capable of removing significant amounts of photosynthetic tissue and causing considerable stem damage. These data, combined with our observations on larval damage to meristems and stem burrowing, suggest that larvae and adults in concert may cause considerable damage to *M. spicatum*. Whether or not weevil feeding can bring about a watermilfoil decline remains to be determined.

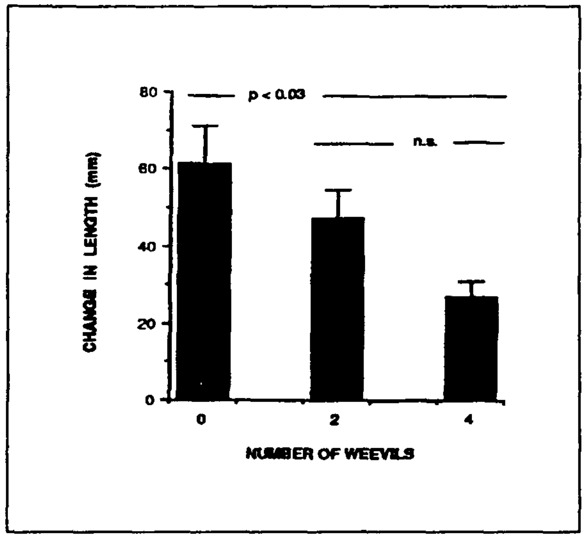
Table 1
Results of the ANCOVA in Which the Adult Effects on Change in Length and Weight, and the Number of Leaves Lost, Are Adjusted for the Presence of Larvae in the Treatments[1]

Response Variable	Type I		Type III	
	F	P	F	P
Length	5.43	0.018	3.54	0.057
Weight	12.43	0.0008	9.35	0.0026
Leaves	20.90	0.0001	19.52	0.0001

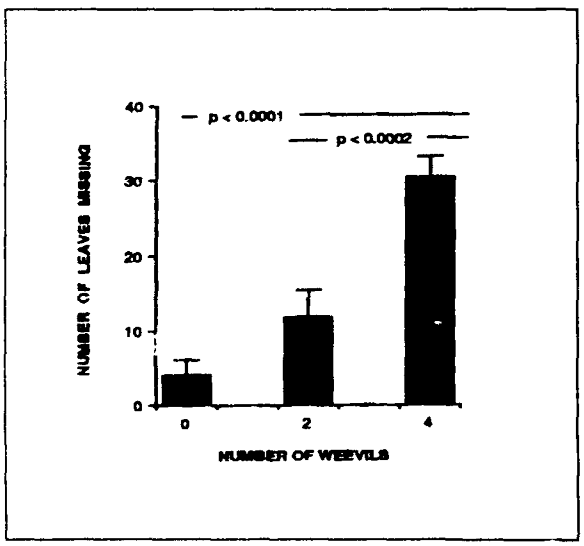
[1] Values in the table are the unadjusted (Type I) and adjusted (Type III) F and P values from the ANCOVA. The F values are for the whole analysis, i.e., all treatments combined, and not the paired contrasts.



a. Change in autofragment weight (in grams)

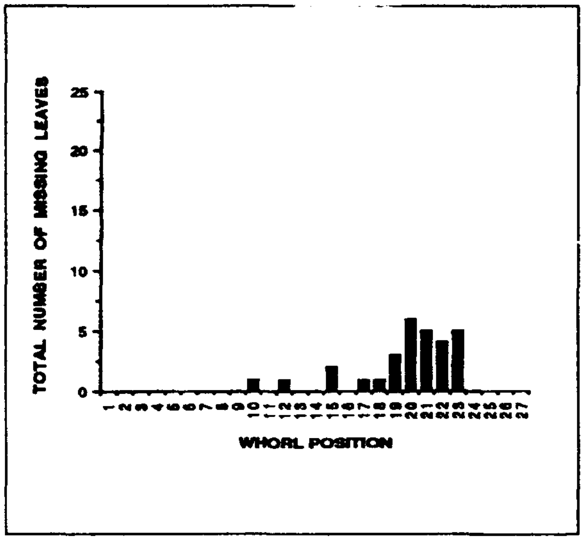


b. Change in autofragment length (in millimeters)

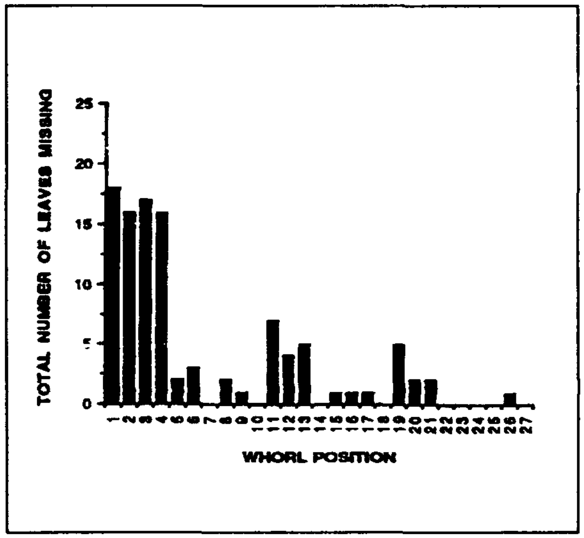


c. Number of leaves lost per autofragment

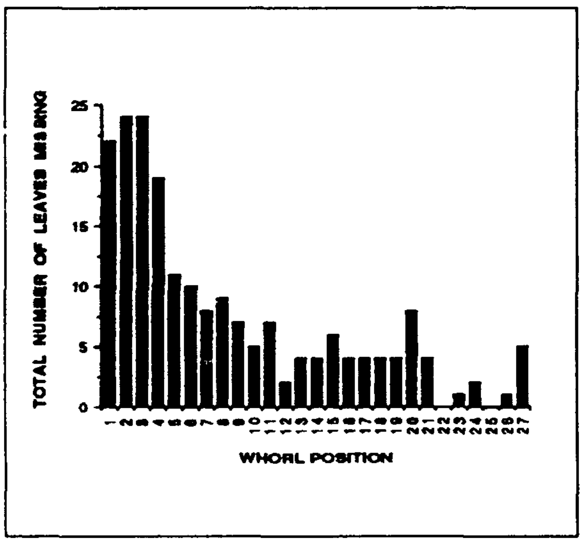
Figure 4. Effect of feeding by adult weevils (E. lecontei) on the growth of watermilfoil autofragments and leaf loss. (Data are from the weevil tube experiment. Bars in histograms represent the mean change in weight (±I ..andard error) for each treatment. Lines with significance values above histograms show results of ANOVA comparisons with orthogonal contrasts. In each figure, the upper line represents the comparison of the control versus the weevil treatments; the lower line represents the comparison of the two- versus the four-weevil treatment)



a. Control treatment (no weevils)

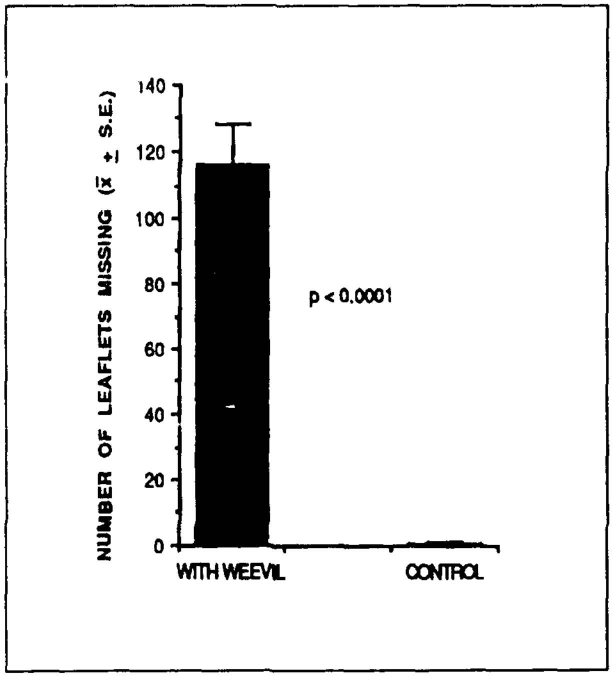


b. Two-weevil treatment

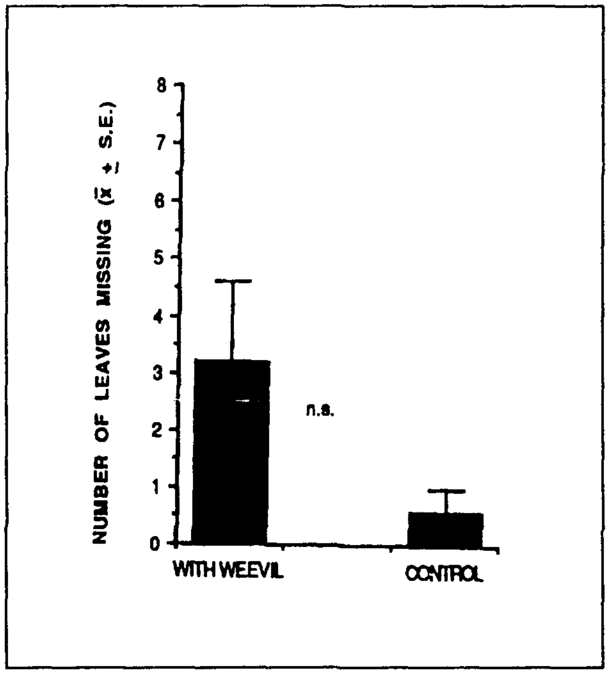


c. Four-weevil treatment

Figure 5. Distribution of leaves removed from watermilfoil autogragments by adult weevils as a function of treatment. Whorl position (x-axis) denotes location of leaves, with 1 being the whorl adjacent to the meristem



a. Leaflet loss



b. Leaf loss

Figure 6. Effects of feeding by adult weevils on leaf loss from watermilfoil stems. (Data are from weevil bag experiment I. Histograms are means (±1 standard error); treatment effects compared with ANOVA)

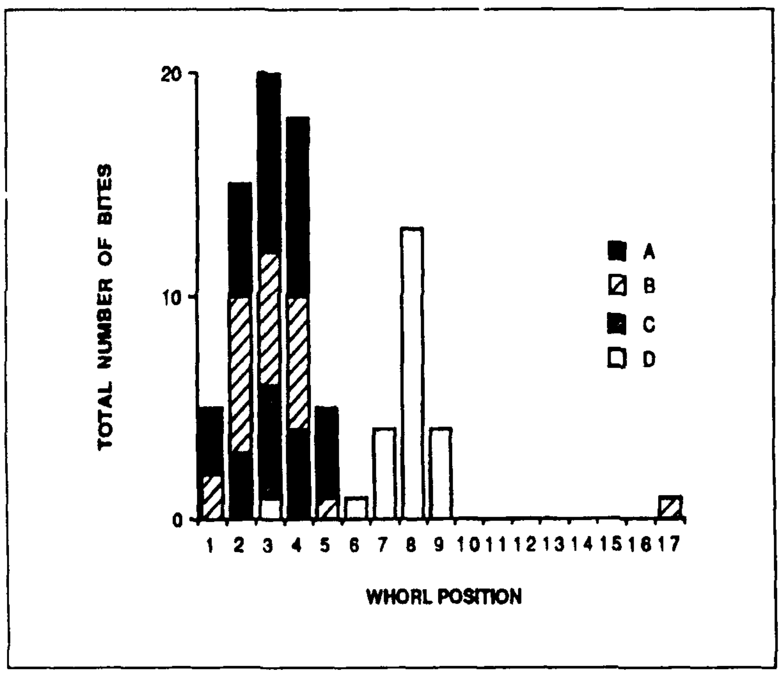
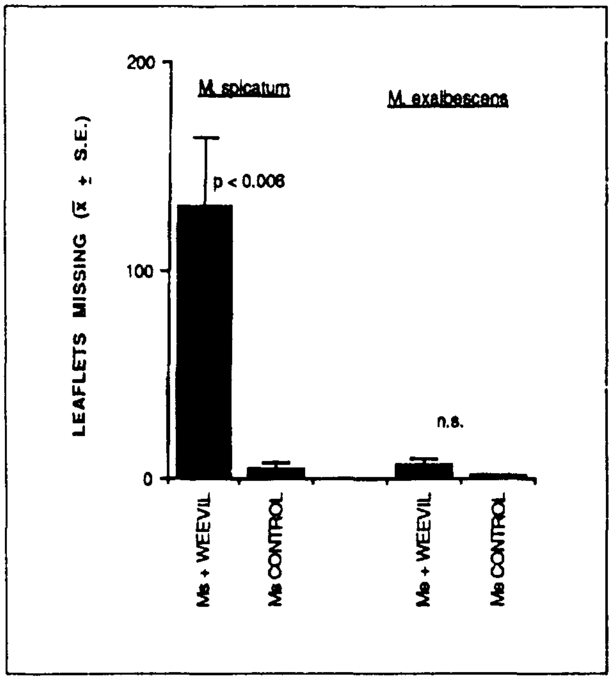
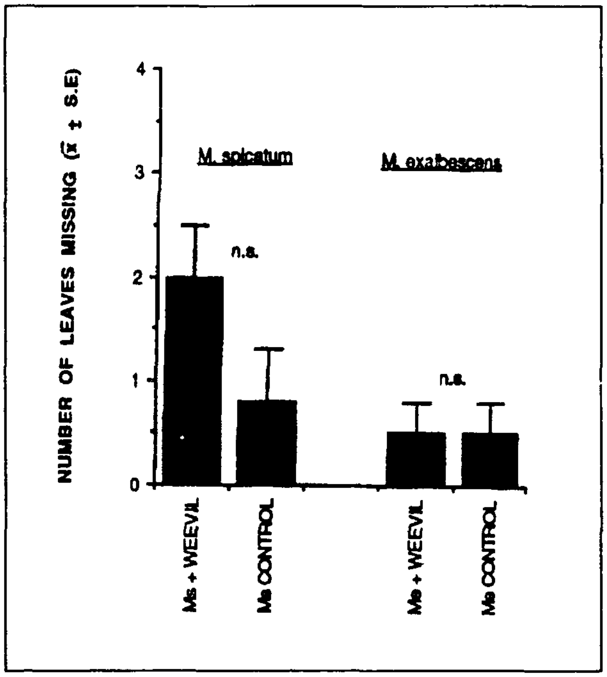


Figure 7. Location of stem bites by four individual adult weevils on watermilfoil stems from weevil bag experiment I. Whorl position (x-axis) denotes the location of leaves, with 1 being the whorl adjacent to the meristem



a. Number of leaflets missing



b. Number of leaves removed

Figure 8. Effects of feeding by adult weevils on leaf loss from both watermilfoil and M. exalbescens stems. (Data are from weevil bag experiment II. Histograms are means (±1 standard error); treatment effects compared with ANOVA)

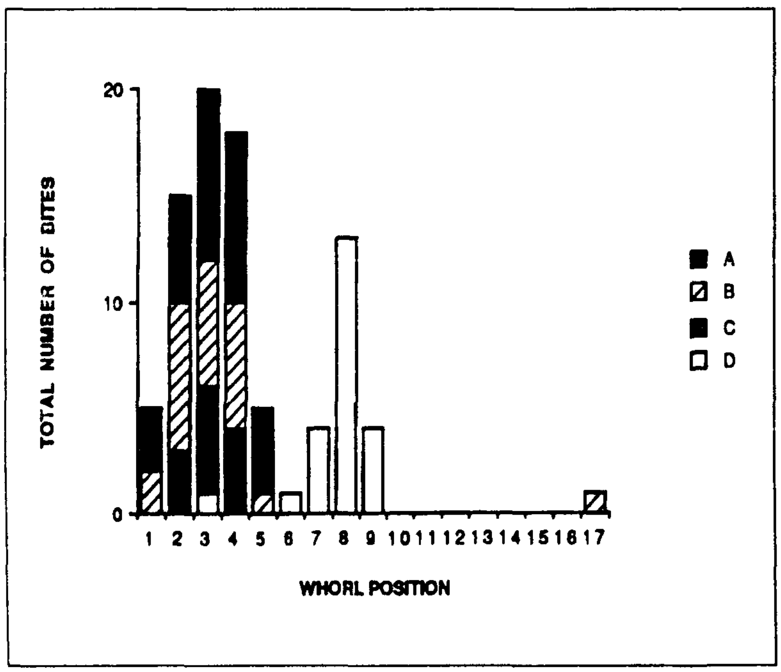


Figure 9. Location of stem bites by four individual adult weevils on M. spicatum (Ms) and M. exalbescens (Me) stems from weevil bag experiment II. Whorl position (x-axis) denotes location of leaves, with 1 being the whorl adjacent to the meristem

Multi-State Lake Survey

In order to determine the distribution of *M. spicatum* herbivores throughout Vermont and part of New England, a number of lakes were visited in 1990. Qualitative surveys were made of watermilfoil (or *Myriophyllum heterophyllum* in New Hampshire) and associated herbivores in these lakes.

Materials and methods

Lists of lakes containing *M. spicatum* populations were obtained from the Vermont Department of Environmental Conservation and the Massachusetts Department of Environmental Protection. A list of lakes with dense populations of *M. heterophyllum* was obtained from the State of New Hampshire. New Hampshire state officials were unaware of any *M. spicatum* populations in their state at that time.

The section of the littoral zone of each lake where milfoil had been previously observed was surveyed by a pair of skin divers. Upon locating the *Myriophyllum*, the plants were examined for the presence of herbivores and evidence of herbivore damage (e.g., *Acentria* day refugia and puparia, grazing scars and internal stem damage from weevils). Specimens of all potential invertebrate herbivores associated with the milfoil were also collected. Dominant plant species in each lake in addition to milfoil were sampled.

Results and discussion

In Vermont, 22 lakes with *M. spicatum* were surveyed. Thirteen of these lakes had *Acentria*, *Eurhychiopsis*, or *Parapoynx*. *Eurhychiopsis lecontei* was found in 10 lakes located throughout the state. *Acentria* and *Parapoynx* were present in eight and four lakes, respectively. Most collections of these herbivores were from lakes in the Champlain Valley drainage on the western part of the state. The two exceptions were Lake Memphremagog and Brownington Pond, which are on the Canadian border. Only one lake from the Connecticut River drainage was examined, and it did not contain these herbivores. Thus, it is too early to say whether any of these herbivores are present in this drainage in Vermont.

Ten lakes were surveyed in western Massachusetts. Three of the lakes had *Acentria*, and three had *E. lecontei*. No *Parapoynx* were found in Massachusetts. The State of Massachusetts also has no records for *Parapoynx* from any of their lakes. All of the lakes surveyed in Massachusetts were in the drainage of the Housatonic River; none were in the Connecticut River drainage.

Eight lakes with "nuisance" populations of *M. heterophyllum* were surveyed in New Hampshire. None of these herbivores were found on this milfoil species in any of the lakes. There are at least three explanations for their apparent absence. First, dispersing herbivores may find *M. heterophyllum*, or other macrophyte species, to be an unsuitable host, and thus may not survive in these lakes. Second, one of more of these herbivores may actually be present in these lakes but, since our divers sampled only *M. heterophyllum*, they were not detected. Third, none of these herbivores may have yet dispersed (with or without human intervention) into New Hampshire.

It is doubtful that the widespread distribution of these herbivores in Vermont is purely the result of unaided dispersal by these animals. We suspect that these herbivores disperse over fairly short distances (up to 5 km) and that this could explain some of the clusters of infested lakes we have observed. With respect to long-distance movements, it is much more likely that these herbivores are often being transported along with watermilfoil plants, especially since both *E. lecontei* and *Acentria* have endophytic life stages. However, the dispersal ability of the adults of these herbivores needs to be investigated.

We noticed in Vermont that the lakes that often did not have herbivores currently have Eurasian watermilfoil control programs. In Lake Bomoseen, where adjacent sections of two watermilfoil beds have been designated

as either harvest or no-harvest areas, we have been evaluating the effect of mechanical harvesting on herbivores. Samples taken at the end of last summer revealed that there was significantly more herbivore damage to unharvested plants compared to harvested ones (Chi square = 1,425.8, 2 df, $p < 0.0001$) at one of the sites. Samples from the other site have not yet been processed.

All three herbivores are often found near the tops of *M. spicatum* plants. Our data on weevil feeding show that adults concentrate their feeding at the tops of plants. Weevil eggs and first instar larvae are found in and on the meristems. Thus, mechanical harvesting may be removing the majority of the weevils (and caterpillars) along with the upper portion of the watermilfoil.

Acknowledgments

We gratefully acknowledge the considerable assistance of Kathy Newbrough, Bill Waddell, Wendy Cox, Holly Crosson, Holly Fryberger, and David Weedman. This work is funded by the US Army Corps of Engineers (contract no. DACW39-90-K-0028), the US Environmental Protection Agency Clean Lakes Demonstration Program, and the Vermont Department of Environmental Conservation.

References

Abrahamsson, S. A. A. 1966. Dynamics of an isolated population of the crayfish *Astacus astacus* Linne. *Oikos* 17:96-107.

Aiken, S. G., Newroth, P. R., and Wile, I. 1979. The biology of Canadian weeds; 34. *Myriophyllum spicatum* L. *Canadian Journal of Plant Science* 59:201-215.

Barko, J. W., and Smart, R. M. 1980. Mobilization of sediment phosphorus by submersed freshwater macrophytes. *Fresh. Biol.* 10:229-238.

Bayley, S., Rabin, H., and Southwick, C. H. 1968. Recent decline in the distribution and abundance of Eurasian milfoil in Chesapeake Bay. *Chesapeake Science* 9:173-181.

Coffey, B. T., and Clayton, J. S. 1988. Contrasting deep-water macrophyte communities in two highly transparent New Zealand lakes and their possible association with freshwater crayfish, *Paranephrops* spp. *New Zealand Journal of Marine and Freshwater Research* 22:225-230.

Couch, R., and Nelson, E. 1986. *Myriophyllum spicatum* in North America. Pages 8-18 in *The First International Symposium on Watermilfoil (Myriophyllum spicatum) and Related Haloragaceae Species.*

Lodge, D. M., and Lorman, J. G. 1987. Reductions in submerged macrophyte biomass and species richness by the crayfish *Orconectes rusticus. Canadian Journal of Fisheries and Aquatic Science* 44:591-597.

Nichols, S., and Cottam, G. 1972. Harvesting as a control for aquatic plants. *Water Resources Bulletin* 8:1205-1210.

Nichols, S. A., and Shaw, B. H. 1986. Ecological life histories of the three aquatic nuisance plants *Myriophyllum spicatum*, *Potamogeton crispus*, and *Elodea canadensis. Hydrobiol.* 131:3-21.

Painter, D. S., and McCabe, K. J. 1988. Investigation into the disappearance of Eurasian watermilfoil from the Kawartha Lakes, Canada. *Journal of Aquatic Plant Management* 26:3-12.

Spencer, N. R., and Lekic, M. 1974. Prospects for biological control of Eurasian watermilfoil. *Weed Science* 22:401-404.

Titus, J. E., and Adams, M. S. 1979. Coexistence and the comparative light relations of the submersed macrophytes *Myriophyllum spicatum* L. and *Vallisneria americana* Michx. *Oecologia* 40:273-286.

Chemical Control Technology

Chemical Control Technology: History and Overview

by
Kurt D. Getsinger[1]

Background

Since the establishment of the Chemical Control Technology Team, this research area has progressed through three major periods: Period I (1975-1978); Period II (1979-1988); and Period III (1989-present). During the first period, the chemical control research effort was directed by Dr. Dana Sanders. Dr. Sander's program responsibilities were shifted to the biological research effort in 1978, and he has since moved into the realm of private consulting.

The second period of chemical control research was led by Dr. Howard Westerdahl, who left the program during 1989 to work for Battelle Pacific Northwest in Richland, WA. Following Dr. Westerdahl's departure, the direction of the chemical technology area was turned over to Dr. Kurt Getsinger.

Although the research emphasis in the chemical area has shifted over time, enough technical continuity has persisted through each period to provide the foundation for the current research approach. Work efforts have concentrated on managing submersed species, primarily Eurasian watermilfoil and hydrilla, since these plants are generally more difficult to control than emergent or floating species.

Prior to providing an overview and update of Period III of the chemical technology area, the major research thrusts and highlights of the first two periods will be discussed.

Period I (1975-1978)

Perhaps the major concern of this early period centered on the registration of aquatic herbicides. Since 1972, all pesticides produced and distributed in the United States have been regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). FIFRA provides for a balance between the risk involved with the use of pesticides and the benefits obtained from their use. As more information was obtained regarding the risks and benefits of each herbicide, fewer herbicides were registered for aquatic use by the US Environmental Protection Agency (EPA).

In addition, the high cost and length of time required for developing and registering new, environmentally compatible aquatic herbicides was resulting in the submission of fewer registrants for EPA approval. These developments were exacerbated by the minor use market of the aquatic arena (as compared to row crops, forestry, etc.). It should be noted that these same factors remain today (1990 estimates for aquatic registration range from $20 to $40 million and 8 to 12 years), and vegetation managers have only a handful of chemical products approved for aquatic use.

In response to this loss of aquatic products, the Chemical Control Team initiated cooperative research and interactions with the EPA, the US Department of Agriculture (USDA), the Tennessee Valley Authority (TVA), the US Bureau of Reclamation

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

(USBR), and the chemical industry to encourage the development and registration of safe and effective aquatic herbicides. This cooperative relationship is still maintained today.

Since potential existed for many of the traditional aquatic herbicides to lose EPA registration (and the aforementioned lack of new registrants entering the market), research efforts during this period focused on improving the effectiveness of remaining products. The premise of this approach was based on the belief that if the number of chemical tools was going to dramatically decrease, the efficacy of the remaining products must be improved (without exceeding the tolerances established for the active ingredients).

Research efforts were therefore directed toward two areas: improving the application of conventional herbicide formulations and initiating the development of controlled-release (CR) herbicide technology. Both of these areas were expanded upon as the second era of the Chemical Control Team began.

Period II (1979-1988)

During this period, work units were established to (1) determine herbicide concentration/exposure time relationships for controlling submersed plants, (2) characterize water-exchange patterns in submersed plant stands to improve control of these plants in flowing-water environments, (3) develop CR herbicide formulations, (4) evaluate synthetic plant growth regulators (PGRs) for controlling submersed plants, and (5) develop an aquatic herbicide use guide for operational personnel.

Concentration/exposure time relationships were developed for 2.4-D and endothall against milfoil, and were initiated for fluridone and endothall against hydrilla. Results from these efforts were used to develop 2,4-D and fluridone CR-formulations, which were tested in the field. Concentration/exposure time information was also used to improve control of submersed plants in flowing water.

Improving the control of submersed plants in high water-exchange environments (e.g. rivers, large reservoirs, canals, tidal areas, etc.) became a central focus of the Chemical Control Team's research efforts at this time. Flow velocity and dye studies were conducted in the field to characterize water movement patterns within stands of milfoil and hydrilla. This information was used to improve and develop submersed herbicide application techniques designed for flowing-water systems.

Also during this period, the first systematic testing of PGRs was undertaken to evaluate their potential for controlling the growth of submersed aquatic plants. A bioassay system was developed under contract, and mesocosm studies were initiated at the US Army Engineer Waterways Experiment Station (WES).

Perhaps the major accomplishment in this era was the publication of a two-volume aquatic herbicide use guide, designed to aid operational personnel in all aspects of the chemical management of aquatic vegetation. Volume I of the guide (a desk reference) provides information on the use and fate of EPA-approved and registered aquatic herbicides, while Volume II is a plant identification and herbicide susceptibility field guide for nuisance floating, emersed, and submersed vegetation.

Most of the work units established during Period II are continuing at the present time. An overview and update of these (and additional) work units is provided below.

Period III (1989-Present): Overview and Update

The broad objective of the chemical control research area is to improve the management of nuisance aquatic plants using herbicides and PGRs in an environmentally compatible manner. A major focus of research is directed toward improving the control of submersed plants in high water-exchange environments. Accomplishment of

these goals requires continued cooperation and coordination with the chemical industry and with various state and Federal agencies, including the EPA Pesticide Registration Branch.

The FY 90 direct-allotted funds for chemical control research were apportioned among five work units, described below.

Herbicide Concentration/Exposure Time Studies (32352)

Research in this area is designed to evaluate EPA-registered, as well as experimental use permit (EUP), chemicals for aquatic sites. This mesocosm-type work is being conducted at the WES under controlled-environment conditions. Eurasian watermilfoil and hydrilla are treated with various herbicides at selected doses and contact times. Results from these studies will be used to establish concentration/exposure time relationships for each herbicide and target plant. Evaluations have been completed with the herbicides 2,4-D, endothall, and triclopyr. Preliminary evaluations have been conducted on milfoil and hydrilla with fluridone. Future studies will include evaluations of fluridone, bensulfuron methyl, diquat, and other appropriate compounds.

Herbicide Application Technique Development for Flowing Water (32354).

In this work unit, submersed application techniques are developed and evaluated to minimize the amount of chemical used and frequency of treatments, while maximizing efficacy against specific target plants. Studies are conducted in large, outdoor flumes or in field situations that exhibit high water-exchange characteristics.

Recent studies have focused on characterizing water movement, and potential herbicide contact time, in submersed plant stands using tracer dyes. Water movement can dramatically impact the dispersion of herbicides from treated plots, as well as the vertical and horizontal distributions of herbicides in the water column. Results from this work can be used by operational personnel to optimize the type and timing of various submersed application techniques.

Water movement studies have been conducted in milfoil stands in California irrigation canals and in the Pend Oreille and Columbia Rivers of Washington State. Similar studies have been conducted in hydrilla stands in the Potomac River, near Washington, DC, and in the Crystal, St. Johns, and Withlacoochee Rivers in Florida.

Submersed application techniques using dyes with liquid, polymer, invert, and granular formulations have been evaluated in Lochloosa Lake and Lake Kissimmee, Florida. Much of this work has been conducted with the cooperation of the University of Florida, as well as various Corps of Engineers Districts and state agencies. Future water movement and application technique studies will be conducted in southeastern and western lakes and rivers.

Herbicide Delivery Systems (32437).

This work unit explores ways to improve herbicide delivery to submersed plants in high water-exchange environments. One focus of the research is directed toward development of controlled-release (CR) carrier systems, e.g. polymers, elastomers, gypsum, fibers, etc. These carriers release herbicides at a slow, predictable rate to the vicinity of the target plant. Reliable information on effective herbicide/concentration exposure times is critical for the development of CR formulations. These required dose/contact time relationships are being provided in the aforementioned Herbicide Concentration/Exposure Time work unit. Future work will include laboratory and field evaluations of potential CR formulations.

In FY 90, dye release rates were evaluated using a gypsum CR formulation, deployed in the Pend Oreille River. In addition, laboratory studies were initiated at the WES to determine 2,4-D, endothall, fluridone, triclopyr, and bensulfuron methyl release rates from various conventional and CR formulations.

Field Evaluation of Selected Herbicides for Aquatic Uses (32404)

The most effective application techniques and chemical formulations are evaluated under large-scale field conditions in this research area. These studies are cooperative efforts among chemical companies, Federal and state agencies, universities, and the WES, with the aim of obtaining environmental fate and dissipation data on EUP herbicides and/or new formulations of registered herbicides. These data are used to prepare field manuals and reports providing recommendations to operational personnel on the activity, use, and application techniques of aquatic herbicides. In addition, chemical companies use this information to fulfill requirements for EPA registration of specific herbicide formulations. Coordination with the EPA is required, since these field evaluations can involve changes in registration status, site use, or amendments of residue tolerances.

During FY 90, the WES conducted field studies to evaluate the efficacy of triclopyr (Renovate) on milfoil, a 27.5-percent active ingredient endothall granule on milfoil and hydrilla, and a liquid formulation of bensulfuron methyl (Mariner) on milfoil and hydrilla. This work was conducted in cooperation with the TVA, Atochem North America, Inc. (formerly Pennwalt), Du Pont, and DowElanco. Similar studies will be conducted in FY 91.

Plant Growth Regulators for Aquatic Plant Management (32578)

Traditional efforts to control nuisance aquatic plants usually destroy the standing crop, often resulting in widespread plant decomposition and disruption of overall community structure. In addition, total removal of plant biomass may result in fluctuations of nutrient levels, turbidity, and dissolved oxygen, with the concomitant loss of habitat dramatically impacting food-web relationships.

Plant growth regulators offer the potential for slowing the vertical growth rate of nuisance submersed plants, thereby reducing the negative impacts that topped-out plants can impose on a water body. Concurrently, the beneficial qualities provided by underwater vegetation (e.g. invertebrate and fish habitat, waterfowl food, oxygen production, nutrient sinks, sediment stabilization, etc.) can be retained. The WES is presently evaluating the potential for using PGRs to manage submersed vegetation.

Bioassay testing of PGR formulations is continuing in cooperation with Purdue University and the USDA Aquatic Plant Laboratory in Fort Lauderdale, FL. The compounds bensulfuron methyl and flurprimidol were evaluated against milfoil and hydrilla in FY 90. These and other products will be evaluated in mesocosm systems in FY 91.

The Improvement of Aquatic Herbicide Delivery Systems

by
Michael D. Netherland[1]

Introduction

In the field, liquid herbicides are often applied in flowing water or in large systems to control submersed vegetation. These applications often result in the rapid dissipation of herbicide from the treatment area. Information from dye/herbicide studies (Fox, Haller, and Getsinger 1990; Getsinger, Haller, and Fox 1990) and from the concentration/exposure time (CET) work (Green 1989, Netherland 1990) suggests that a lack of chemical contact time may be responsible for the failure of many herbicide treatments. The ability to keep the herbicide within the area of treatment for a longer period of time would improve efficacy, and possibly would allow for the use of less active ingredient in the area treated (i.e. lower concentrations over longer exposure times).

This relationship between the length of time a submersed macrophyte is exposed to a given concentration of herbicide and target plant injury is supported by the work of weed physiologists. These researchers suggest that a minimum amount of herbicide must be absorbed into living plant tissues to cause plant death. This is also referred to as the critical tissue burden (Holly 1976, Ashton and Crafts 1981, Ross and Lembi 1985).

The key for successfully controlling submersed plants with chemicals in high-water exchange environments is maintaining an adequate herbicide exposure period. It is clear that a need exists to develop herbicide formulations and/or delivery techniques that will extend chemical contact time to improve control of submersed vegetation. This knowledge has led some researchers to study the possibility of controlling the release of herbicides in water to lengthen contact time (Steward and Nelson 1972, Van and Steward 1986).

One approach to slowly releasing herbicides is through a controlled- release (CR) matrix. A CR matrix or formulation is defined as an active ingredient of a pesticide (herbicide, insecticide, plant growth regulator, etc.) combined with an inert carrier (e.g. polymer, lignin, clay, etc.). Harris, Norris, and Post (1973) stated that, in addition to providing long-term control, CR formulations (a) minimize pesticide residues available to the environment, (b) maintain toxic concentrations of pesticides in close proximity to the target organism, (c) increase the efficacy and longevity of the pesticide by protecting it from environmental degradation, and (d) decrease application costs since less frequent applications are required.

Each herbicide has a unique concentration and exposure time requirement against a specific target plant. Information that defines CET relationships of herbicides against specific target plants is vital for the successful development of CR matrices. One general trend that has been consistent throughout the CET studies is that as exposure time is increased, lower concentrations of herbicide are required to achieve plant control. Based upon this trend, researchers are of the opinion that low herbicide concentrations and increased exposure times will allow them to focus on a delivery-systems target area to achieve plant control (Figure 1).

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

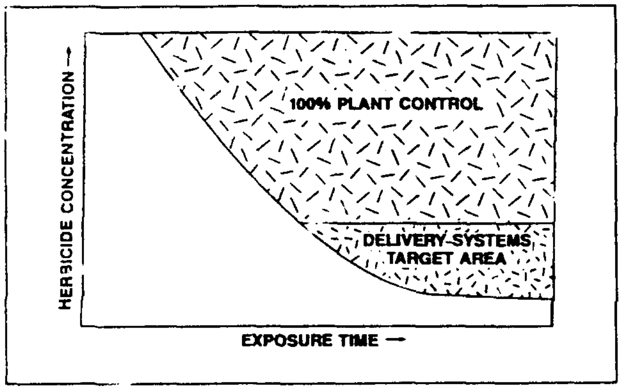


Figure 1. Target area for herbicide delivery systems. Note the requirement for low herbicide concentration and increased exposure time

Internal herbicide tissue burden information should also be quite valuable for the development of CR matrices. Research by Haller and Sutton (1973), Reinert et al. (1985), Van and Steward (1986), and Van and Conant (1988) has shown that, with many aquatic herbicides, only a small proportion of the herbicide in the water is taken up by the plant (Table 1). These results indicate that plant uptake rates are often quite slow, and extending contact time should improve efficacy.

Table 1
Internal Tissue Burden

Investigators	Herbicide	Target Species	Herbicide in Plant Tissue (Lethal Amount)
Van and Conant (1988)	Endothall	Hydrilla	~7%
Haller and Sutton (1973)	Endothall	Hydrilla	~6%
Van and Steward (1986)	Fluridone	Hydrilla	~3%
Reinert et al (1985)	Endothall	Milfoil	~3%

In addition, promising new CR technologies are emerging in the area of aquatic insect control. These technologies could prove useful for the chemical control of submersed plants. Gypsum- and protein-based products have been developed to release the mosquito larvicide Altosid (methoprene) for a period of up to 60 days. The ability of these matrices to release insecticides in an aquatic environment over an extended period of time and approval for field use of the gypsum compound by the US Environmental Protection Agency are encouraging.

A resurgence of environmental concern by the public has stimulated a demand for reducing the loading of pesticides into the environment. Developing technologies designed to deliver herbicides in the most efficient manner to target plants offers the potential of using less active ingredient to achieve greater efficacy. This approach ultimately translates into enhanced herbicide efficacy, lower treatment costs, and better environmental compatibility.

Objectives

The objectives of this work unit are to develop and evaluate delivery systems that will maximize herbicide contact time against submersed macrophytes within a treatment area.

Research Approach

Improved herbicide delivery systems will be developed and evaluated over the next several years, with initial efforts focusing on CR matrices. The following approach will be used to conduct the CR studies:

- Environmentally compatible CR delivery systems will be identified and selected for evaluation. Emphasis will be placed on matrices that have shown the ability to slowly release pesticides in an aquatic environment.

- Once identified, matrices will be formulated with a variety of aquatic herbicides (e.g., fluridone, triclopyr, bensulfuron methyl, 2,4-D, and endothall) to test for compatibility between the matrix and the active ingredient of the herbicide.

- Successfully formulated herbicide matrices will be evaluated in the laboratory

to determine if controlled release is feasible with the matrix being tested. Release rates of the newly developed CR formulations will be compared with release rates of conventional granular formulations.

- Information developed from CET and internal tissue burden studies will be used to design release rate profiles for individual herbicides against the target species.

- Matrices that release herbicides within design specifications will be further evaluated for efficacy against Eurasian watermilfoil and hydrilla in laboratory, mesocosm, and pond studies.

Herbicide Release Rate Studies

Studies are being conducted at the Waterways Experiment Station to evaluate herbicide release rates from conventional and CR formulations. Conventional formulations tested include granular 2,4-D (Aqua Kleen), fluridone (Sonar SRP), and endothall (Aquathol). A 27.5-percent active ingredient, granular formulation of endothall was also tested. Two CR matrices have been formulated for evaluation: gypsum-based and protein-colloid matrices containing 2,4-D, triclopyr, fluridone, and bensulfuron methyl. Measured amounts of active ingredient of each formulation were added to 50-L aquaria, and residue samples were collected over an 8-day period.

The objectives of this initial phase of testing are to determine the compatibility of new CR matrices with individual herbicides, and to test for the ability of these matrices to slowly release active ingredients. Based upon laboratory performance, the most promising formulations will be further developed for release-rate testing.

Acknowledgments

The author wishes to thank Controlled Release Systems Research, Inc., for the CR formulations, and Atochem, DowElanco, Du Pont, Rhone-Polenc, and the Tennessee Valley Authority for supplying active ingredients and conventional formulations used in this study. The author also wishes to express thanks to Glenn Turner for technical assistance.

References

Ashton, F. M., and Crafts, A. S. 1981. *Mode of action of herbicides*, 2nd ed. John Wiley and Sons, New York.

Fox, A. M., Haller, W. T., and Getsinger, K. D. 1990. Dye studies in submersed plant stands in moving water. Pages 134-137 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Getsinger, K. D., Haller, W. T., and Fox, A. M. 1990. Herbicide application techniques for flowing water: Evaluation of submersed techniques using Rhodamine WT. Pages 128-133 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Green, W. R. 1989. Herbicide concentration/exposure time studies on Eurasian watermilfoil. Pages 106-110 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Haller, W. T., and Sutton, D. L. 1973. Factors affecting uptake of endothall-^{14}C by hydrilla. *Weed Sci.* 21:446-448.

Harris, F. W., Norris, S. O., and Post, L. K. 1973. Factors influencing release of fenac from polyethylene matrices. *Weed Sci.* 21:318-321.

Holly, K. 1976. Selectivity in relation to formulation and application methods. Pages 249-275 in *Herbicides: Physiology, Biochemistry, Ecology*, L. J. Audus, ed. Academic Press, New York.

Netherland, M. D. 1990. Herbicide concentration/exposure time relationships: Endothall/hydrilla and triclopyr/Eurasian watermilfoil. Pages 110-114 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*, Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Reinert, K. H., Rodgers, J. H., Hinman, M. L., and Leslie, T. J. 1985. Compartmentalization and persistence of endothall in experimental pools. *Ecotoxicology and Environ. Safety* 10:86-96.

Ross, M. A., and Lembi, C. A. 1985. *Applied Weed Science*. Burgess Publishing, Minneapolis, MN.

Steward, K. K., and Nelson, L. L. 1972. Evaluations of controlled release PVC and attaclay formulations of 2,4-D on Eurasian watermilfoil. *Hyacinth Control J.* 10:35-38.

Van, T. K., and Conant, R. D. 1988. Chemical control of hydrilla in flowing water: Herbicide uptake characteristics and concentrations versus exposure. Technical Report A-88-2. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van, T. K., and Steward, K. K. 1986. The use of controlled-release fluridone fibers for the control of hydrilla (*Hydrilla verticillata*). *Weed Sci.* 34:70-76.

Herbicide Concentration/Exposure Time Relationships for Eurasian Watermilfoil and Hydrilla

by
Michael D. Netherland[1]

Introduction

The efficacy of a herbicide application to nuisance submersed plants is related to the length of time the target species is exposed to dissipating concentrations of the herbicide. Chemical treatments are often applied to systems in which off-target movement results in a rapid dissipation of the herbicide. For example, the length of time a herbicide will remain within the treatment area can be dictated by physical conditions such as water flow (velocity), wind-induced water movement, or thermal stratification (Fox, Haller, and Getsinger 1990; Getsinger, Haller, and Fox 1990). The rate of herbicide dissipation can ultimately determine the success or failure of a chemical treatment.

Development of the functional relationship between herbicide concentrations and exposure times will provide information that will be useful in predicting situations in which a herbicide treatment may succeed or fail.

Concentration/exposure time (CET) relationships are being developed for each registered aquatic herbicide because of the unique properties (e.g., mode of action, rate of application, environmental half-lives, plant uptake rates, plant growth stage, and plant susceptibility) of the herbicides with respect to the target species. Development of CET relationships has included the evaluation of 2,4-D, endothall, and triclopyr against the nuisance submersed dicot Eurasian watermilfoil (*Myriophyllum spicatum* L.), and endothall and fluridone against the nuisance submersed monocot hydrilla (*Hydrilla verticillata* (L.f.) Royle).

A better understanding of the effect that herbicide CET relationships have on efficacy may lead to improved formulations or application techniques in systems where reduced contact time presents a problem. The development of these relationships will also provide guidance for operational personnel in making the best use of herbicides in the field.

Objective

The objective of this work unit is to identify, in the laboratory, the effective ranges of aquatic herbicide concentrations and exposure times that control Eurasian watermilfoil (hereafter referred to as milfoil) and hydrilla.

Materials and Methods

Independent studies of 2,4-D, endothall, and triclopyr versus milfoil and of endothall and fluridone versus hydrilla were conducted in controlled-environment systems previously described by Green (1989) and Netherland (1990). Temperature was maintained at 24° ± 2° C, with a photoperiod of 13L:11D. Mean photosynthetically active radiation, measured at the water surface, ranged from 450 to 580 $E \times m^{-2} \times sec^{-1}$. Treatments (herbicide concentration × exposure time) were randomly assigned to 55-L aquaria, with three replications for each treatment. Each aquarium was independently supplied with a continuous flow of simulated hard water solution (Smart and Barko 1984), except when herbicide exposures were being conducted.

Four apical shoots (12 to 15 cm in length) were planted in 300-ml beakers containing sediment. Sediment was obtained from

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Brown's Lake, Waterways Experiment Station, and was amended with macro- and micronutrients (Rapid Gro) to eliminate possible nutrient limitations during the course of the study. A thin layer of silica sand was placed on top of the sediment to prevent resuspension of sediment. Eleven beakers containing the planted apical shoots of the target species were then placed in each aquarium.

Plants were allowed to grow approximately 3 weeks prior to herbicide treatment. This pretreatment growth period allowed plants to reach the water surface and ensured the development of a healthy, viable root system. One beaker was randomly removed from each aquarium prior to herbicide treatment to provide an estimate of treated biomass.

Calculated concentrations of the herbicides were applied to the designated aquaria. (The flow-through system was turned off during the treatment and exposure period.) At the end of the assigned exposure times, aquaria were drained and refilled three times to remove the remaining herbicide residues. Water samples were taken immediately after treatment (to verify treatment concentrations), at the end of the required exposure time (to determine herbicide dissipation), and after the final rinse (to verify residue removal).

Plants were allowed to grow 4 to 6 weeks posttreatment. Plant control was determined by comparing the harvested biomass (separated into shoots and roots) obtained from each treatment. Weekly visual evaluations were used to characterize the initial response and progression of injury symptoms of the herbicide-treated plants compared with untreated reference plants. Visual evaluations were also used to determine the time at which healthy regrowth began to occur after treatment.

Results and Discussion

Data obtained from harvested biomass were used in conjunction with visual injury evaluations to produce relationships that predict herbicide injury based on varying levels of concentrations and exposure times tested. CET combinations resulted in varying levels of plant injury that increased with increasing concentrations and/or exposure times.

As concentrations and exposure times were increased from levels that resulted in >95-percent control, plant control increased. As evidenced by the graphs presented, CET combinations that fall below these levels result in decreasing levels of plant control as concentrations and exposure times are decreased (as shown in Figures 1-4). This trend was observed for all herbicides tested on the target plants.

Results of the 2,4-D/milfoil study indicated that concentrations of 2.0 mg acid equivalent (ae)/L for 36 hr and 1.0 mg ae/L for 48 hr were required to give >95-percent milfoil control (Figure 1). A concentration of 0.5 mg ae/L for 72 hr (maximum exposure time tested) resulted in ~80-percent milfoil control.

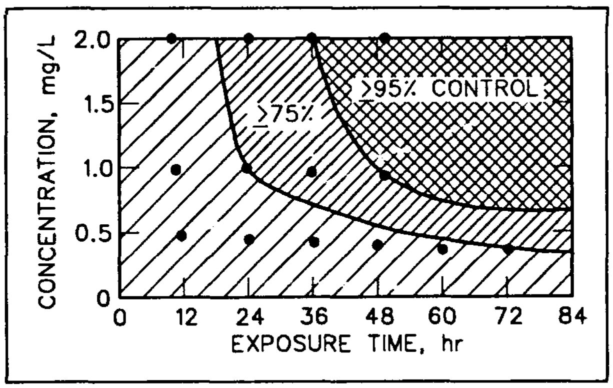


Figure 1. 2,4-D concentration and exposure time relationships for control of Eurasian watermilfoil. (Circles represent actual 2,4-D concentration/exposure times tested)

Results of the endothall/milfoil study showed that concentrations of 5.0 mg ae/L for 12 hr, 3.0 mg ae/L for 24 hr, 1.0 mg ae/L for 48 hr, and 0.5 mg ae/L for 72 hr were required to give >95-percent milfoil control (Figure 2). Treatments of 1.0, 3.0, and 5.0 mg ae/L for 2 hr were ineffective. Plant injury following these treatments was minimal, resulting in healthy and rapid regrowth.

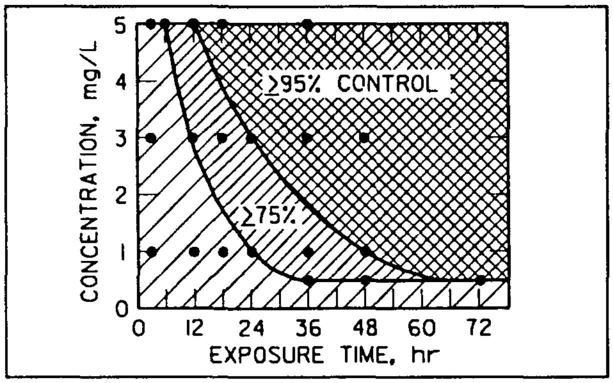


Figure 2. Endothall concentration and exposure time relationships for control of Eurasian watermilfoil. (Circles represent actual endothall concentration/ exposure times tested)

Preliminary results of the triclopyr/milfoil study indicate that concentrations of 2.5 mg ae/L for 18 hr, 2.0 mg ae/L for 24 hr, 1.5 mg ae/L for 30 hr, 1.0 mg ae/L for 36 hr, and 0.5 mg ae/L for 60 hr were required to give >95-percent milfoil control (Figure 3). These preliminary results indicate that triclopyr may be slightly more effective than 2,4-D (at equal treatment rates) in controlling milfoil.

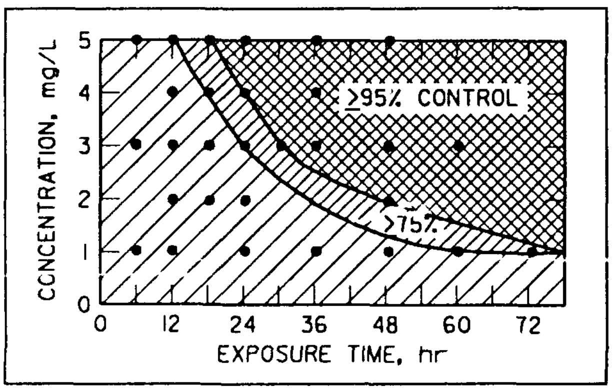


Figure 3. Triclopyr concentration and exposure time relationships for control of Eurasian watermilfoil. (Circles represent actual triclopyr concentration/ exposure times tested)

The endothall/hydrilla study required concentrations of 5.0 mg ae/L for 18 hr, 4.0 mg ae/L for 24 hr, 3.0 mg ae/L for 30 hr, and 2.0 mg ae/L for 48 hr to achieve 95-percent hydrilla control (Figure 4). The 1.0 mg ae/L for 72 hr resulted in ~75-percent hydrilla control. Treatments of 1.0, 3.0, and 5.0 mg ae/L for 6 hr, and 1.0, 2.0, and 3.0 mg ae/L for 12 hr showed few signs of visual injury and resulted in little biomass reduction (5 to 20 percent).

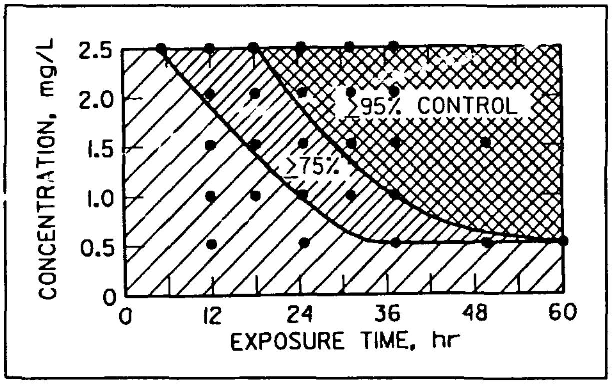


Figure 4. Endothall concentration and exposure time relationships for control of hydrilla. (Circles represent actual endothall concentration/ exposure times tested)

The fluridone/hydrilla study differed significantly from the previously mentioned studies, in that exposure times were measured in days instead of hours and concentrations were reduced to micrograms per liter. Hall and Westerdahl (1984) reported that up to 70 days of continuous exposure to 20 µg active ingredient (ai) fluridone/liter was required to achieve >95-percent hydrilla control (Figure 5). Due to slow uptake rates, the efficacy of fluridone treatments in the field has been greatly improved when fluridone exposure times (at concentrations of 10 to 25 µg ai/L) are increased.

Current fluridone studies are aimed at further defining the CET combinations required for hydrilla control. Preliminary results of recently conducted static treatments indicate that 25 and 50 µg ai/L at 21 days of exposure were insufficient in significantly reducing hydrilla biomass (Table 1). Treated hydrilla was injured and stunted when in contact with fluridone; however, upon fluridone removal, plants began to regrow vigorously from rootcrowns. Results indicate that exposure

times of >21 days should be tested to increase hydrilla efficacy.

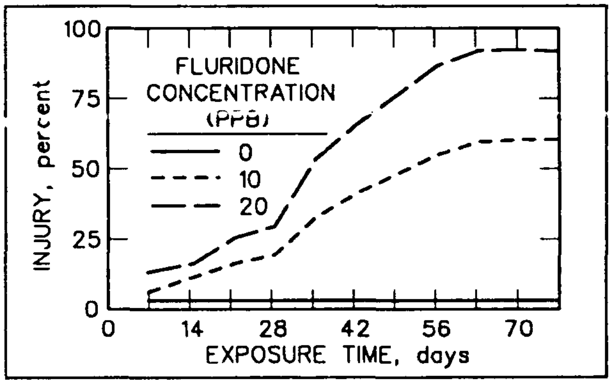


Figure 5. Response of hydrilla to two continuous fluridone concentrations over a 77-day exposure period

Table 1
Fluridone Versus Hydrilla

Concentration, ppb	Exposure Time, Days	% of Reference Shoot Mass at 6 WAT	% of Reference Root Mass at 6 WAT
100	3 7	75 72	112 96
50	7 14 21	65 63 60	96 92 81
25	7 14 21	64 68 67	89 92 84

Note: WAT = Weeks after treatment.

It should be noted that exposure times in the field will differ from the static exposures conducted in the laboratory; that is, plants in the field will be exposed to a dissipating concentration of herbicide over time. In addition, the ability of field plants to produce large rootcrowns may make them more tolerant to herbicide treatments than laboratory-grown plants. Therefore, the direct application of laboratory results to field situations should be viewed with some degree of caution.

Information obtained from CET studies is most useful when coupled with an accurate ability to predict herbicide dissipation in the field. The use of a dye study to determine potential herbicide dissipation or half-lives presents a new, relatively inexpensive method to predict potential contact time (Fox, Haller, and Getsinger 1990; Getsinger, Haller, and Fox 1990).

Based upon the potential contact time, CET relationships could be used to provide guidance for the most effective use of a compound and rate of application in hydrodynamic systems. The choice of the correct herbicide and application rate is important for both economic and environmental reasons.

Future work will include the completion of the triclopyr/milfoil studies. The bensulfuron methyl and fluridone studies on hydrilla and milfoil will be initiated.

Acknowledgments

The author would like to thank Mr. Reed Green, Gay Nell White, Nancy Craft, and Brian York for laboratory assistance. The cooperation of Atochem North America, Inc., and DowElanco, Inc., in providing herbicide and residue analysis is greatly appreciated.

References

Fox, A. M., Haller, W. T., and Getsinger, K. D. 1990. Dye studies in submersed plant stands in moving water. Pages 134-137 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Getsinger, K. D., Haller, W. T., and Fox, A. M. 1990. Herbicide application techniques for flowing water: Evaluation of submersed techniques using Rhodamine WT. Pages 128-133 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Green, W. R. 1989. Herbicide concentration/exposure time studies on Eurasian watermilfoil. Pages 106-110 *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hall, J. F., and Westerdahl, H. E. 1984. Growth response of *Myriophyllum spicatum* and *Hydrilla verticillata* when exposed to continuous, low concentrations of fluridone. *J. Aquat. Plant Manage.* 28:27-32.

Netherland, M. D. 1990. Herbicide concentration/exposure time relationships: Endothall/hydrilla and triclopyr/Eurasian watermilfoil. Pages 110-114 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program,* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Smart, R. M., and Barko, J. W. 1984. Culture methodology for experimental investigation involving rooted submersed aquatic plants. Miscellaneous Paper A-84-6. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Herbicide Application Technique Development for Flowing Water: Relationship of Water Exchange and Submersed Application Methods

by

Kurt D. Getsinger,[1] Charles Hanlon,[2] Joseph C. Joyce,[2] Alison M. Fox,[2] and William T. Haller [2]

Introduction

Research in this work area focuses on the development and evaluation of conventional and innovative application techniques for controlling submersed plants in high-water exchange environments. Since 1988, investigators from the Waterways Experiment Station and the University of Florida Center for Aquatic Plants have been studying water exchange patterns in submersed plant stands in reservoirs, lakes, rivers, and canals using fluorescent dye (Fox, Haller, and Getsinger 1988, 1989, 1990; Getsinger, Green, and Westerdahl 1990; Getsinger, Haller, and Fox 1990). The objectives of this work are to (a) characterize flow velocities and water exchange in submersed plant stands under field conditions and (b) evaluate application techniques that maximize herbicide contact time in flowing-water environments.

This paper presents preliminary results of three studies designed to evaluate submersed application techniques and potential herbicide contact time. Results of the first study describe the retention time of the fluorescent dye Rhodamine WT in monoecious hydrilla stands in tidal coves and flats in the Potomac River near Washington, DC. Results of the second study describe the retention time of Rhodamine WT in Eurasian watermilfoil stands in the Pend Oreille and Columbia Rivers, Washington. In the third study, four submersed application techniques are compared using Rhodamine WT in dioecious hydrilla stands in Lake Kissimmee, Florida.

Potomac River Study

Materials and methods

In September 1989, Rhodamine WT was applied to three river plots near the Woodrow Wilson Bridge (Interstate Highway 95) and to a fourth plot located within the marina cove at Bolling Air Force Base (BAFB) on the Potomac River (Figure 1). Plots directly north and south of the bridge were 4 ha (10 acres); the cove plot, south of the bridge, was 0.8 ha (2 acres). The BAFB marina plot, north of the bridge, was 1.2 ha (3 acres).

Dye was mixed with 470 L of water per hectare (50 gal/acre) and applied as a tank mix (to achieve a dye concentration of 10 µg/L throughout the plot) using short hoses mounted to the stern of an airboat. Hydrilla formed a continuous mat across the surface at low tide in, and around, all of the river plots; however, little hydrilla was present in the BAFB marina plot.

Nine dye sampling stations were established in the north and south river plots, and 16 additional stations were established at 30 and 100 m outside the treatment area (Figure 2). Six stations were established in the cove plot, and eight in the BAFB marina plot (Figure 3). Dye concentration and water

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] University of Florida Center for Aquatic Plants, Gainesville, FL.

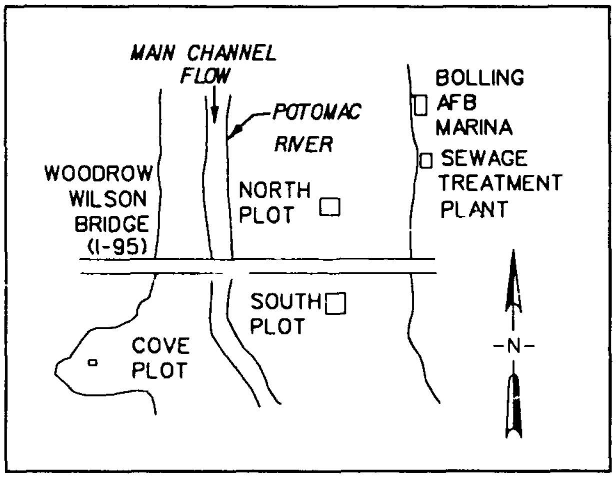


Figure 1. Location of dye-treated plots in the Potomac River near Washington, DC

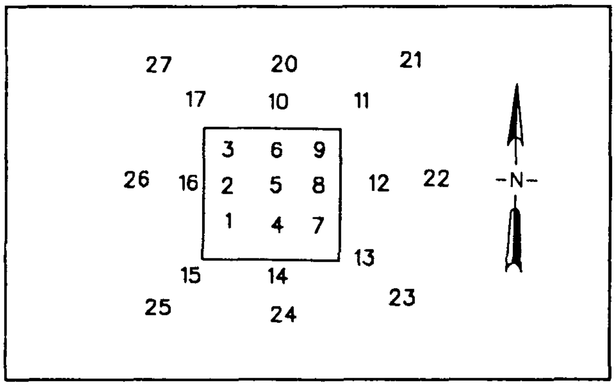
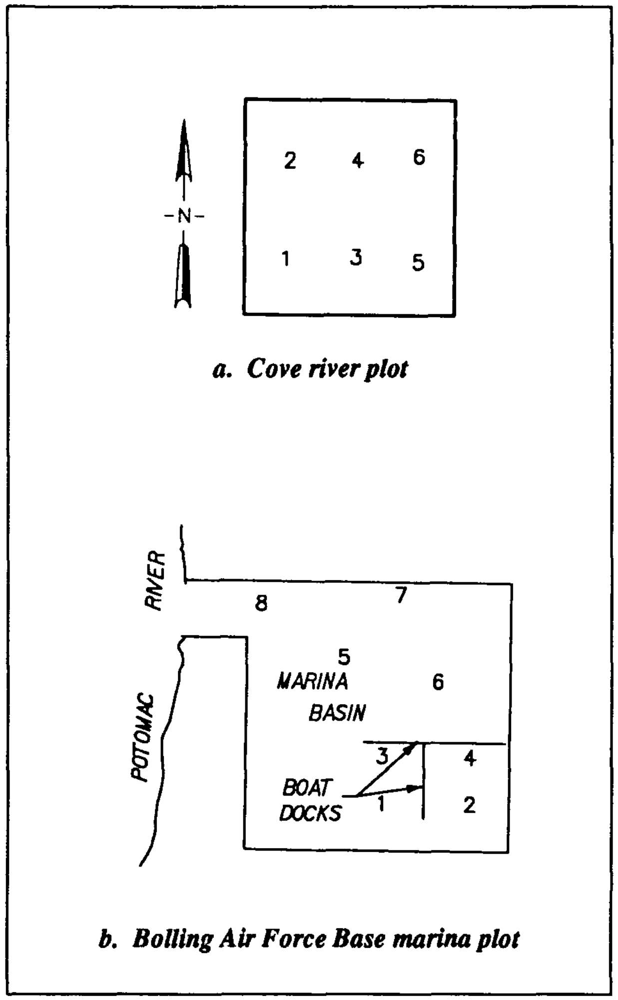


Figure 2. Location of dye sampling stations for north and south river plots



a. Cove river plot

b. Bolling Air Force Base marina plot

Figure 3. Location of dye sampling stations for cove river and marina plots

temperature were measured simultaneously at each station, during high tide at 0.25-m intervals from the river bottom to the surface. Dye was monitored using a Turner Design model 10-005 field fluorometer fitted with a high-volume, continuous-flow cuvette system; water temperature was monitored using a thermocouple thermometer.

The north and south plots were monitored for 67 hr posttreatment, while the cove and BAFB marina plots were monitored for 44 hr posttreatment. Dye half-lives were calculated by regressing the natural logarithms of the dye concentrations (averaged from all stations within the plot) over a minimum of four sampling times.

Results

Water temperature differences between bottom and surface waters were similar in all plots. These differences ranged from 0° to 2.1° C; however, there was generally less than 0.5° C difference between surface and bottom zones (Table 1). Although there were differences between plots, all plots tended to have a relatively short dye half-life: 7.2 hr (minimum) and 11.4 hr (maximum). Half-lives of this duration could present problems in providing sufficient hydrilla control using conventional aquatic herbicide formulations and application techniques.

Table 1
Average Temperature Readings (°C) in the Potomac River North Plot, September 1989

Station	Hours After Treatment: 4	18	30	42	67
	Time of Sampling: 1730	0700	1830	0700	0800
Surface	26.2	25.2	25.7	25.1	24.1
Bottom[1]	25.9	24.8	25.3	24.8	23.8

[1] Readings taken 0.25 m above the river bottom.

Table 2
Average Dye Concentrations (μg/L) in the North Plot of the Potomac River, September 1989

Hours After Treatment	Depth	Stations 1-3	4-6	7-9	Plot Average
4	Surface[1]	0	8.2	16.1	
	Bottom[2]	0	3.7	10.1	
	Column avg.	0	5.7	13.7	6.6
17	Surface	0	0	0	
	Bottom	0	0.45	3.3	
	Column avg.	0	0.18	1.14	0.43
30	Surface	0	0.03	0.16	
	Bottom	0	0.22	1.2	
	Column avg.	0	0.13	0.53	0.23
42	Surface	0	0	0	
	Bottom	0.05	0.13	0.36	
	Column avg.	0.02	0.05	0.17	0.08
67	Surface	0	0	0	
	Bottom	0	0.02	0.08	
	Column avg.	0	0.01	0.03	0.01

[1] Average of readings taken at the surface and 0.25 m below.
[2] Average of readings taken at 0.25 and 0.5 m above the river bottom.

North river plot. The north river plot averaged 1.5 m in depth and had a dye half-life of 7.2 hr (Figure 4). Initial data showed that dye was not uniformly distributed within the treatment area; thus, the nine sampling stations were divided into three groups for further analysis. Stations 1 through 3 represented the west side of the plot; stations 4 through 6, the center; and stations 7 through 9, the east side.

Four hours after treatment, dye concentrations averaged 5.7 and 13.7 μg/L at the center and eastern stations, respectively; however, no dye was found at stations 1-3. During this time, dye concentrations in the plot generally ranged from 6 to 15 μg/L at the surface and were <6 μg/L near the bottom. Dye dissipated from the plot in a westerly direction via the weed-free surface waters at high tide, with initial dye loss being greatest along the southwestern portion of the plot. Here, surface dye concentration at station 15 (30 m from the southwest corner of the plot) was 9.5 μg/L.

After 17 hr, dye was not detected at stations 1, 2, 3, 5, or 6, and was not present at any surface station within the plot. The greatest concentration of dye, 5.4 μg/L, was found near the bottom at station 7; however, the average dye concentration for the entire water column at station 7 was only 1.75 μg/L. The largest average dye concentrations outside the plot occurred at stations 12 (1.4 μg/L) and 23 (1.3 μg/L), 30 and 100 m east and southeast of the plot, respectively. At 42 hr posttreatment, most of the dye had dissipated from the plot; by 67 hr posttreatment, dye was generally nondetectable within the plot (Table 2).

South river plot. The south plot averaged 1.4 m in depth and had a dye half-life of 11.4 hr (Figure 4). Initial data showed that dye was not uniformly distributed within the plot (Table 3). Dye concentrations were always greatest along the west side of the plot (as opposed to the east side of the north plot). Since dye concentrations within the plot were stratified from east to west, stations 1-9 were divided into the three groupings previously mentioned.

Four hours after treatment, the average dye concentration in the south plot was 6.2 μg/L. The dye dissipated from the plot in a westerly to southwesterly direction. Stations 1-3 had the highest dye concentration (10.3 μg/L), followed by the three center and eastern stations, with concentrations of 6.6 and 1.6 μg/L, respectively. As noted in the north plot, dye dissipated from the plot in the upper 0.5 m of the water column. The highest average concentrations found outside the plot were at stations 16 (11.5 μg/L) and 15 (3.6 μg/L). These plots had surface concentrations of 22.4 and 9.5 μg/L, respectively.

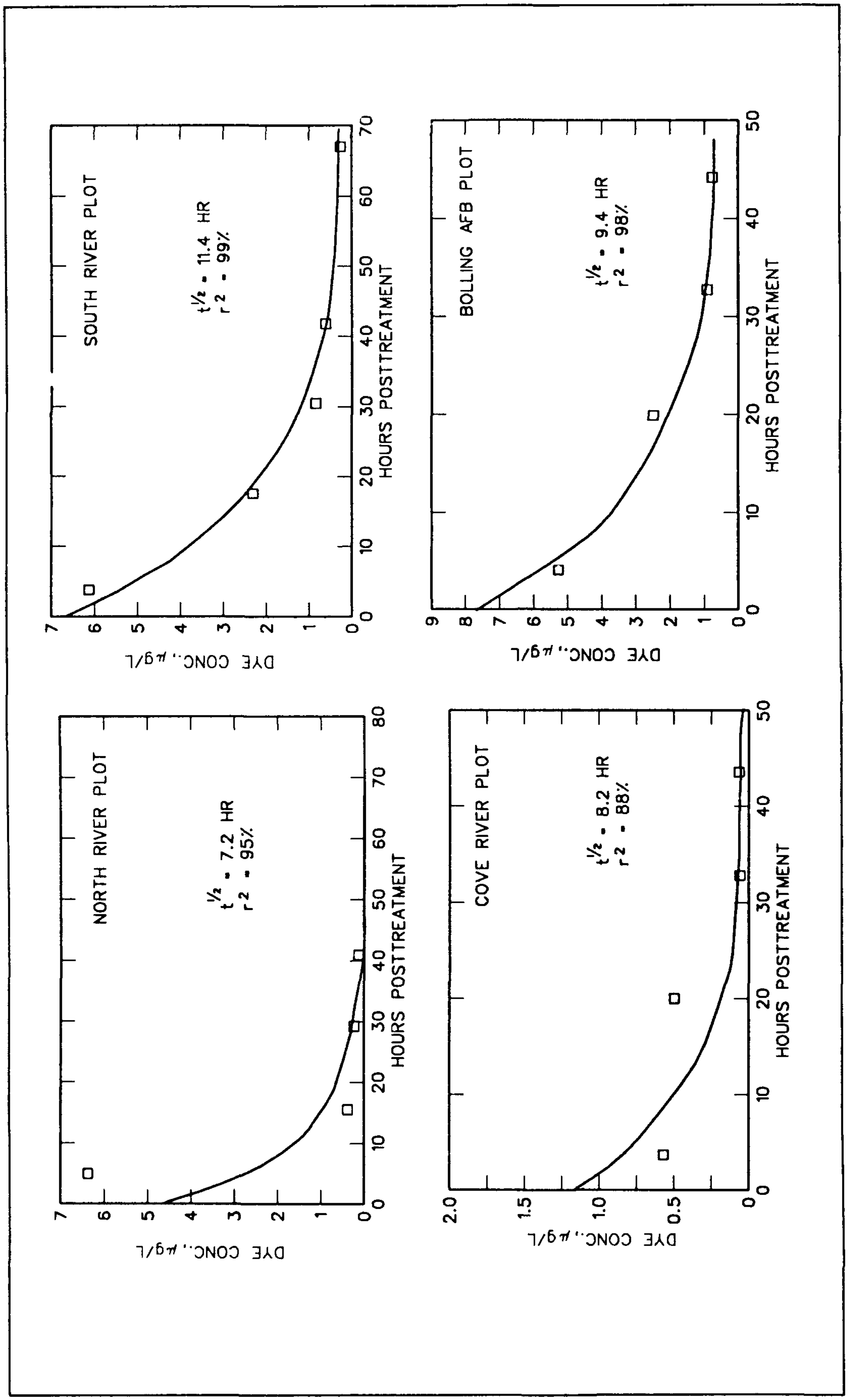


Figure 4. Dye concentrations in river plots and BAFB plot

Table 3
Average Dye Concentrations (µg/L) In the South Plot of the Potomac River, September 1989

Hours After Treatment	Depth	Stations 1-3	4-6	7-9	Plot Average
4	Surface[1]	12.5	4.5	0.28	
	Bottom[2]	7.1	9.4	3.2	
	Column avg.	10.3	6.6	1.6	6.2
17	Surface	0.11	0.03	0	
	Bottom	9.1	6.7	1.45	
	Column avg.	3.8	2.53	0.56	2.3
30	Surface	0.06	0.04	0	
	Bottom	5.6	2.1	0.23	
	Column avg.	2.1	0.74	0.1	0.96
42	Surface	0	0	0	
	Bottom	2.9	1.4	0.48	
	Column avg.	1.0	0.48	0.17	0.55
67	Surface	0	0	0	
	Bottom	0.65	0.25	0.06	
	Column avg.	0.24	0.1	0.02	0.12

[1] Average of readings taken at the surface and 0.25 m below.
[2] Average of readings taken at 0.25 and 0.5 m above the river bottom.

Most of the dye had dissipated from the east side of the plot by 17 hr posttreatment, with remaining dye found near the bottom. The average concentration in the west side of the plot was six times greater than that found in the east side, as dye continued to exit the plot in a westerly to southwesterly direction. Dye concentrations averaged 2.5 µg/L at station 15 and 1.6 µg/L at stations 16 and 26. The maximum dye concentrations measured at these stations (station 15 = 7.5 µg/L; station 16 = 6.3 µg/L; station 26 = 4.8 µg/L) occurred near the bottom in the dense hydrilla mat.

The average dye concentration of the south plot after 42 hr was only 0.55 µg/L. After 67 hr, all stations had dye concentrations of <1 µg/L, and any remaining dye was found near the bottom (Table 3).

Cove river plot. The cove plot averaged 1.3 m in depth, and the dye half-life within the plot was 8.2 hr (Figure 4). Initial data, recorded 4 hr posttreatment, showed that dye concentrations were much lower in this plot compared with the other river plots (Table 4).

Table 4
Average Dye Concentrations (µg/L) In the Cove Plot and the Bolling Air Force Marina, Potomac River, September 1989

Plot	Station	Hours After Treatment 4	20	33	44
Cove	Surface	0.70	0.40	0	0
	Bottom	0.81	0.58	0.1	0.1
	Plot Avg.	0.62	0.48	0.05	0.03
Bolling AFB Marina	Surface	4.9	1.6	0.76	0.29
	Bottom	5.6	2.9	0.38	0.31
	Plot Avg.	5.2	2.3	0.59	0.29

Dye concentrations ranged from a maximum of 1.5 µg/L at station 2 to a minimum of 0.1 µg/L at station 6. Dissipation of the dye was slow during the first 20 hr posttreatment; yet, by the second day (33 hr), almost all the dye had moved out of the plot. Only trace amounts of dye were measured at either the 33- or 44-hr sampling period, and remaining dye was located near the bottom.

BAFB marina plot. The BAFB marina plot averaged 2.8 m in depth and had a dye half-life of 9.4 hr (Figure 4). Initial dye distribution was more uniform in this plot compared with the river plots. At 4 hr posttreatment, this plot had an average dye concentration of 5.2 µg/L (Table 4). There was little variance between stations in this plot, and levels ranged from a low of 4.6 µg/L at station 1 to a high of 6.1 µg/L at stations 4 and 6. At the 20- and 33-hr sampling periods, dye concentrations tended to be greatest at stations 1-4 (i.e., stations farthest from the marina/river interface). During the 4- and 20-hr sampling period, dye concentrations were greatest near the bottom, averaging 5.6 and 2.9 µg/L, respectively.

After 33 hr, dye concentrations at stations 5-8 were fairly uniform, top to bottom, with all values being <0.5 µg/L. In the more protected northeast area of the plot (stations 1-4), dye concentrations were greatest near the surface, where values were ≥1.2 µg/L. By 44 hr posttreatment, a uniform, vertical distribution occurred throughout the plot, with average surface and bottom dye concentrations equaling 0.29 and 0.31 µg/L, respectively.

Pend Oreille and Columbia Rivers Study

Materials and methods

In August 1990, Rhodamine WT was applied to three 10-acre plots on the Pend Oreille and Columbia Rivers (Figure 5). These plots were dominated by dense stands of Eurasian watermilfoil. One Pend Oreille River treatment site (Plot PR-61, mean depth 1.7 m) was located approximately 0.5 km upstream from river mile 61, between the western shore of the river and the island directly to the east. The second Pend Oreille treatment site (Plot PR-LCB, mean depth 1.8 m) was situated within Lost Creek Bay, approximately 0.3 km downstream and northwest of river mile 48.

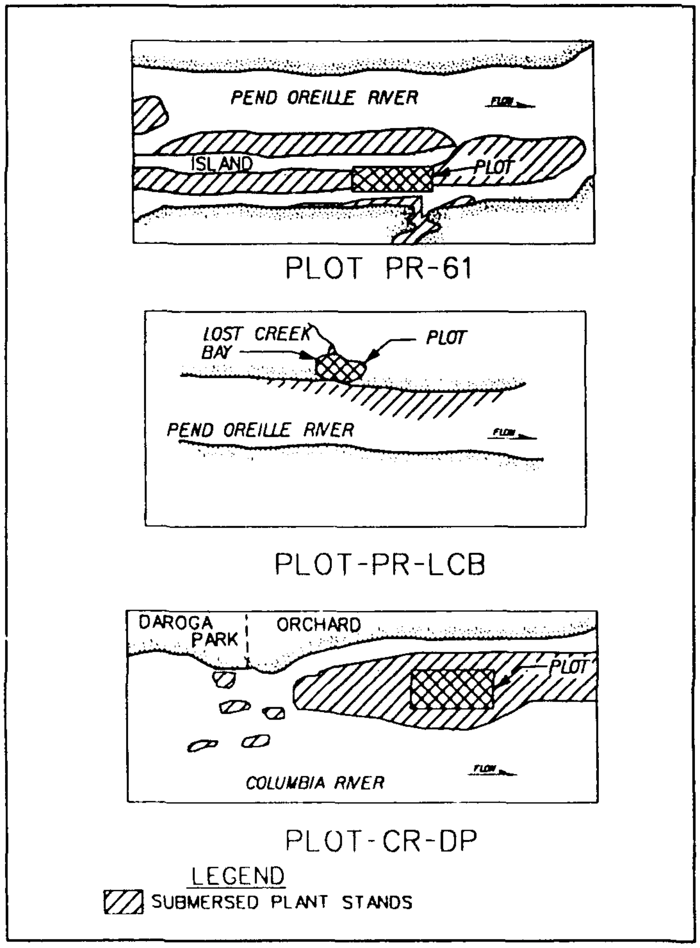


Figure 5. Dye plots on Pend Oreille and Columbia Rivers

The Columbia River treatment (Plot CR-DP, mean depth 1.5 m) was located 20 km upstream from the Rocky Reach Dam, approximately 0.5 km downstream from the southern boundary of Daroga Park, near the eastern shore of the river. The dye was tank mixed with river water and applied to achieve a concentration of 10 µg/L dye throughout the plots, using short hoses mounted on the stern of an airboat.

Five sampling stations were established in each plot, and dye concentrations and water temperature were measured simultaneously using a fluorometer and thermometer as described above. Dye was monitored at 0.25-m intervals from the surface to the bottom of each station for 12 hr posttreatment in Plot PR-61, 120 hr posttreatment in Plot PR-LCB, and 30 hr posttreatment in Plot CR-DP. Dye half-lives were calculated as described above.

Results

Pend Oreille River plots PR-61 and PR-LCB. As expected, dye dissipated at an accelerated rate from the riverine plot (PR-61) and at a slow rate from the protected cove plot (PR-LCB). The dye half-life in Plot PR-61 was calculated at 7.8 hr, whereas the dye half-life in Plot PR-LCB was calculated at 38.8 hr (Figure 6). These half-lives suggest the potential for successful plant control in PR-LCB, but insufficient plant control in Plot PR-61, using conventional aquatic herbicide formulations and application techniques.

Columbia River plot CR-DP. As dye was being applied to Plot CR-DP, the water discharge rate from Rocky Reach Dam (approximately 22 km downstream from the plot) was being increased due to peak demand for electrical power generation. This resulted in a rapid dissipation of dye from the eastern side of the plot, which was adjacent to a deep (>3 m) weed-free channel. Consequently, the calculated dye half-life for

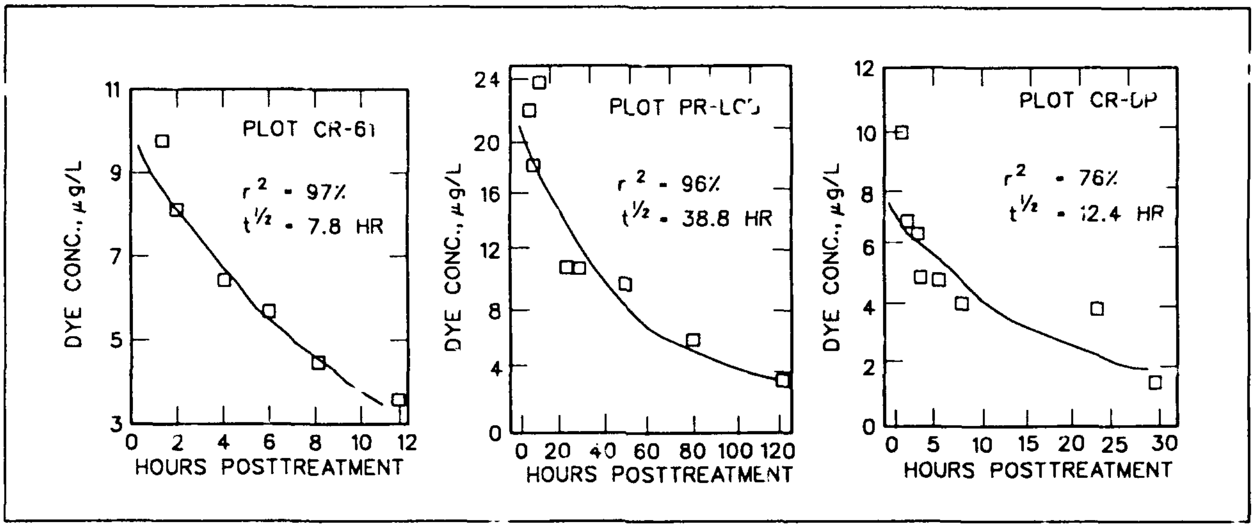


Figure 6. Dye concentrations in Pend Oreille and Columbia river plots

Plot CR-DP was 12.4 hr (Figure 6), suggesting the potential for inadequate herbicide contact time and insufficient plant control. However, when dye dissipation from the plot was determined using data from stations that were not severely impacted by the drawdown, the calculated half-life was 35 hr (regression not shown), suggesting adequate herbicide contact time and efficacy. These results emphasize the importance of coordinating drawdown schedules with submersed herbicide applications.

Lake Kissimmee Study

Materials and methods

Submersed application technique evaluations were conducted in dense stands of dioecious hydrilla in Lake Kissimmee during the second week of May 1990. Twelve 0.4-ha (1-acre) plots were established in three sites at the northern end of the lake in water approximately 2 m deep (Figure 7). The hydrilla stands were in a surface-matted condition, and stratified water temperatures existed in the stands. Four application techniques (three replicates each) were evaluated using Rhodamine WT (Table 5). The techniques used for preparation and application of dye formulations, and for measurement of dye concentrations, were as described in Getsinger, Haller, and Fox (1990).

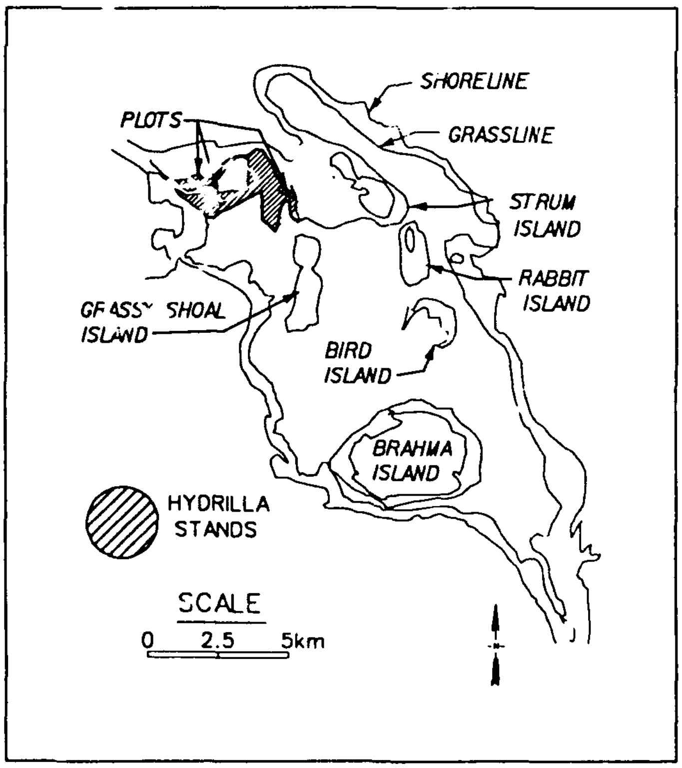


Figure 7. General location of dye plots on Lake Kissimmee, Florida, May 1990

Table 5 Submersed Application Techniques Evaluated at Lake Kissimmee, May 1990	
Plot Number	**Application Technique**
3, 5, 9	Liquid
2, 8, 12	Polymer
1, 7, 11	Invert + copper
4, 6, 10	Granule

Results

Changes in percent distribution of dye in the water column following application with the various techniques are shown in Table 6.

Table 6
Percent Dye in Top and Bottom Halves of the Water Column in Plots Treated with Various Application Techniques, Lake Kissimmee

Hours Post-treatment	Technique	Percent Dye: Top	Percent Dye: Bottom
2	Liquid	95	5
	Polymer	95	5
	Invert + copper	77	23
	Granule	77	23
8	Liquid	96	4
	Polymer	96	4
	Invert + copper	82	18
	Granule	77	23
24	Liquid	63	37
	Polymer	81	19
	Invert + copper	28	72
	Granule	48	52

In general, the granules provided the most evenly distributed dye concentrations throughout the water column during the study, while the polymer and liquid applications provided the poorest dye distribution. Posttreatment dye distribution was similar when using liquid and polymer techniques. At 2 and 8 hr posttreatment, most of the dye in these plots remained near the surface, with little distribution to the bottom half of the water column. Water column distribution was somewhat better in the liquid versus the polymer treatments by 24 hr posttreatment. The invert plus copper and the granule treatments showed similar water column distributions at 2 and 8 hr after application; however, the invert application provided a greater bottom distribution of remaining dye at 24 hr posttreatment.

Future Work

Studies planned for FY 91 will continue to focus on evaluation of submersed application techniques using dyes and herbicides. Companion studies will determine the relationships between the dissipation of Rhodamine WT and aquatic herbicides in submersed plant stands.

Acknowledgments

The authors express appreciation for the technical assistance, and support, provided to the Potomac River dye study by the USAE District, Baltimore; the Washington, DC, Council of Governments; Messrs. Eddie "Gorilla" Knight and George "[illegible]" Gallagher, USAE District, Jacksonville; Mr. M. Turtora, USGS; Ms. Margaret Glenn, Center for Aquatic Plants; and Mr. Mike Netherland and Dr. Howard Westerdahl, WES.

Technical assistance and support during the Washington State dye studies were provided by Mr. Bob Rawson and the USAE District, Seattle; Mr. Dave Sisneros and Ms. Stephenie Smink, US Bureau of Reclamation; Mmes. Kathy Hamel and Stefani Bouchele and Mr. Allen Moore, Washington Department of Ecology; and personnel of the Albeni Falls Project Office and Aquatics Unlimited, Inc. Appreciation is also extended to Mr. Glenn Turner, WES, for statistical analysis of the data from these studies.

We appreciate the assistance of the operational and technical crews from the St. Johns River and South Florida Water Management Districts and the Center for Aquatic Plants, as well as the support of the USAE District, Jacksonville, during the Lake Kissimmee study.

References

Fox, A. M., Haller, W. T., and Getsinger, K. D. 1988. Preliminary study of the dilution of dyes in tidal canals of the Crystal River, Florida. Pages 195-201 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fox, A. M., Haller, W. T., and Getsinger, K. D. 1989. Factors affecting the dispersion of dyes in tidal canals in the Crystal River, Florida. Pages 103-105 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fox, A. M., Haller, W. T., and Getsinger, K. D. 1990. Dye studies in submersed plant stands in moving water. Pages 134-137 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Getsinger, K. D., Green, W. R., and Westerdahl, H. E. 1990. Characterization of water movement in submersed plant stands. Miscellaneous Paper A-90-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Getsinger, K. D., Haller, W. T., and Fox, A. M. 1990. Herbicide application techniques for flowing water: Evaluation of submersed techniques using Rhodamine WT. Pages 128-133 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Field Evaluation of Selected Herbicides

by
Kurt D. Getsinger[1]

Introduction

The research goals of this work unit are to evaluate the effectiveness of recently registered and experimental use permit (EUP) aquatic herbicide formulations in the field. Generally, these studies are cooperative efforts among industry, Federal and state agencies, universities, and the US Army Engineer Waterways Experiment Station (WES). Data generated in these large-scale studies can be used by chemical companies to fulfill requirements for US Environmental Protection Agency (EPA) registration (or reregistration) of specific herbicide formulations.

In fiscal year (FY) 90, herbicide field studies included evaluation of a new, more concentrated endothall granule, and continuation of the bensulfuron methyl EUP study. Updates of these studies are presented below.

Field Evaluation of 27.5-Percent Endothall Granules

Several years ago, Atochem North America, Inc. (formerly Pennwalt), developed a new dipotassium salt endothall granule with an active ingredient (ai) content of 27.5 percent. This new loading process results in an approximate 60-percent reduction in the amount of formulation required for submersed aquatic plant control, when compared to the standard 10.1-percent ai endothall granular formulation, known as Aquathol. For example, if a situation dictated that 100 lb (40 kg) of the standard Aquathol formulation were required to achieve a given concentration of endothall in the water, only 38 lb (25 kg) of the new 27.5-percent ai formulation would be needed to achieve an identical water concentration of endothall.

In addition to reduction of material required for treatment (which is an important consideration for applicators), this new product has been formulated to minimize dust problems associated with conventional granular applications.

In June 1990, several 10-acre plots were established in Guntersville Reservoir, Alabama, to evaluate the efficacy of the 27.5-percent ai endothall granules on Eurasian watermilfoil and hydrilla. These studies were conducted in cooperation with the TVA and Atochem. Unfortunately, the Guntersville area experienced prolonged periods of abnormal weather during the study. Rains throughout the watershed resulted in deep, turbid water conditions that interfered with scheduled efficacy evaluations. Hence, results of the endothall treatments were inconclusive.

These field trials will be repeated in FY 91 and will include collection of herbicide dissipation data to be used in support of EPA registration of the 27.5-percent endothall formulation.

Cooperative Mariner (Bensulfuron Methyl) EUP Studies

The data-collection phase of an intensive three-site EUP study designed to determine the fate and dissipation of Du Pont's aquatic herbicide bensulfuron methyl (trade name, Mariner) was completed in 1989. The University of Florida's Center for Aquatic Plants conducted closed-pond dissipation and accumulation studies near Welaka, FL, while the

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

US Bureau of Reclamation and the WES conducted field dissipation studies in Banks Lake, Washington, and Lake Seminole, Georgia, respectively. Field study cooperators also included the US Army Engineer District, Mobile; Aquatics Unlimited; the Georgia Department of Natural Resources; and the Washington Department of Ecology.

Concurrent laboratory and field efficacy studies of bensulfuron methyl against Eurasian watermilfoil and hydrilla are being conducted by the USDA in Davis, CA, and Fort Lauderdale, FL; by the University of Florida in Gainesville and Welaka, FL; by the TVA and WES in Guntersville Reservoir; and by the WES in Vicksburg, MS.

Extensive herbicide residue analyses (including water, sediment, fish, crayfish, and clams) are being conducted by Morse Laboratories, Inc., of Sacramento, CA. Final reports are scheduled for completion in FY 91. Information from these reports will be used by Du Pont to support the EPA aquatic registration of bensulfuron methyl.

Future Work

Future field studies will concentrate on efficacy and dissipation of bensulfuron methyl, triclopyr, fluridone, and endothall. Large-scale triclopyr trials, based on results from studies conducted in the Herbicide Concentration/Exposure Time work unit, are planned for Guntersville Reservoir in FY 91 and for the Pend Oreille River, Washington, in FY 92.

Plant Growth Regulators for Aquatic Plant Management

by
Linda S. Nelson,[1] Thai K. Van,[2]
Carole A. Lembi,[3] Tara Chand[3]

Introduction

Chemical control strategies to manage nuisance aquatic plants emphasize the use of nonselective aquatic herbicides. This type of herbicide use severely reduces or eliminates most of the plants in the area of treatment. New technologies, such as the use of plant growth regulators (PGRs), may provide an alternate management option in the near future, that of suppressing or inhibiting plant growth rather than removing it.

Plant growth regulators are synthetic compounds that, when applied to plants, alter or interfere with various growth processes, such as reduced stem elongation through inhibition of the plant hormone gibberellin. Perhaps PGRs can eliminate plant "weediness" by keeping vegetation short while still allowing them to remain as a functional part of the aquatic ecosystem.

The overall objective of this work unit is to evaluate PGR activity on nuisance aquatic plant species and to determine the feasibility of utilizing PGRs as a management strategy. Research is currently being conducted by Purdue University, the USDA Aquatic Plant Management Laboratory, and the US Army Engineer Waterways Experiment Station (WES).

Studies at Purdue University were the first to be initiated to identify the feasibility of using PGRs for aquatic plant management. Most recently, efforts have focused on the following:

- Determining efficacy and duration of exposure for stem length reduction in hydrilla and Eurasian watermilfoil using flurprimidol, a gibberellin synthesis inhibitor.
- Determining longevity of the gibberellin synthesis inhibitor flurprimidol, in soil, plant tissue, and water.
- Screening other compounds for potential growth regulating effects on hydrilla and Eurasian watermilfoil, using a previously developed laboratory bioassay method.

Studies at the USDA Aquatic Plant Management Laboratory and at the WES were both directed at further evaluation of bensulfuron methyl on hydrilla and Eurasian watermilfoil. Bensulfuron methyl is currently registered by Du Pont as a herbicide (Londax) for use in rice production and shows potential as a herbicide and growth regulator (when used at lower rates) for management of submersed aquatic plants. Of all the potential growth-regulating products evaluated thus far, bensulfuron methyl is nearest to receiving aquatic registration.

The following sections provide updates on each of the research efforts described above.

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] US Department of Agriculture Aquatic Plant Management Laboratory, Fort Lauderdale, FL.
[3] Purdue University, West Lafayette, IN.

Bioassay of Plant Growth Regulator Activity on Aquatic Weeds (Purdue University)

Materials and methods

Outdoor tank studies. Studies were conducted in metal or plastic barrels (67-L capacity), with plastic liners. Fertilized loam soil (free from PGRs, herbicides, and pesticides) was added to a 10-cm depth in each barrel. Approximately 55 L of well water was added, and the suspended soil was allowed to settle. Healthy Eurasian watermilfoil plants were collected from a nearby pond and rinsed free of epiphytes and dirt. Two 15-cm apical stem sections (with intact growing point) were planted in each barrel. The plants were allowed to acclimate to the barrels for 5 days.

Treatments were applied on 1 June 1990 and consisted of 0, 75, and 200 µg/L ai (active ingredient) flurprimidol. Each treatment was replicated twice. Treated plants were exposed for 2 and 24 hr and 3, 7, 14, and 28 days. At the end of each exposure period, the water in the barrel was removed and replaced with fresh, untreated water. Plants were allowed to recover for 4 weeks posttreatment. At that time, the following measurements were taken: main stem length, number and length of lateral branches, and shoot and root fresh and dry weights.

Water, sediment, and plant tissue samples were also collected at each time interval (prior to replacing the treated water) for later gas chromatograph and mass spectrophotometer (GC/MS) testing for flurprimidol residues.

A similar barrel experiment was established for hydrilla. Hydrilla plants were grown in the laboratory under controlled conditions prior to planting. Treatments consisted of 0, 75, and 750 µg/L ai flurprimidol and were begun on 31 July 1990. The plants were exposed to flurprimidol for 1, 2, and 24 hr and 3 days.

At the end of each exposure period, water in the barrel was removed and replaced with fresh, untreated water. Plants were allowed to recover for 5 weeks posttreatment. At that time, the following measurements were taken: main stem length, stolon number and length, number and length of lateral branches, and fresh and dry weight. No samples were taken for flurprimidol analysis from this experiment.

Laboratory bioassays. Bioassay techniques used were those described previously by Lembi and Netherland (1989). All compounds tested were from formulated product and included the herbicides bensulfuron methyl, imazapyr, imazaquin, and imazethapyr and the growth regulator amidochlor (Limit).

Two types of experiments were conducted with bensulfuron methyl: long-term exposure and duration of exposure. For long-term exposure, Eurasian watermilfoil was exposed to 0, 0.6, 6.0, and 60 µg/L ai for 4, 6, and 8 weeks. A concentrated source of inorganic nutrients was added at intervals to ensure that the plants had sufficient nutrients for growth during the long-term exposures.

For duration of exposure, Eurasian watermilfoil was exposed to 60 µg/L ai bensulfuron methyl for 2, 12, and 24 hr and 3, 7, 14, and 28 days. At the end of each of these exposure periods, the plants were removed from the treatment, rinsed thoroughly, and placed in fresh, untreated medium for a 4-week recovery period.

Imazapyr, imazaquin, imazethapyr, and amidochlor were tested for growth effects on hydrilla and Eurasian watermilfoil at different concentrations. For hydrilla, concentrations of imazapyr were 0, 1, 5, 7.5, 10, and 25 µg/L ai; concentrations of imazaquin and imazethapyr were 0, 5, 10, 25, 50, and 100 µg/L ai. Concentrations of amidochlor were 0, 10, 50, 100, 500, and 1,000 µg/L ai. For Eurasian watermilfoil, concentrations tested were 0, 5, 10, 50, 100, and 500 µg/L ai for imazapyr and imazaquin; 0, 10, 50, 100, 500 and 1,000 µg/L ai for imazethapyr; and 0, 50, 100, 250, 500, and 1,000 µg/L ai for amidochlor.

Prior to these treatments, the range of concentrations was chosen by prescreening each species and compound at 0, 1, 10, 100, and 1,000 µg/L ai. Treatments were for 4 weeks and were replicated three times. Measurements were taken on main stem length, lateral stem length and number, root length and number, photosynthesis rate, respiration rate, and fresh and dry weight.

Results

Outdoor tank studies with flurprimidol and Eurasian watermilfoil. Excellent results were obtained at 200 µg/L flurprimidol with 31 percent reduction in main stem length observed after a 2-hr exposure. The plants at this concentration, and at all exposure times, were significantly reduced in main stem length (at the 0.05-percent level) (Figure 1). These plants appeared bushy and very healthy. The total length (calculated by adding all main stem and lateral stem lengths), root and shoot fresh weights, and dry weights were also reduced at each exposure time at 200 µg/L. The number of lateral stems that emerged was somewhat inconsistent, but it appeared that there was not much difference in the number of laterals between control plants and plants treated at 200 µg/L.

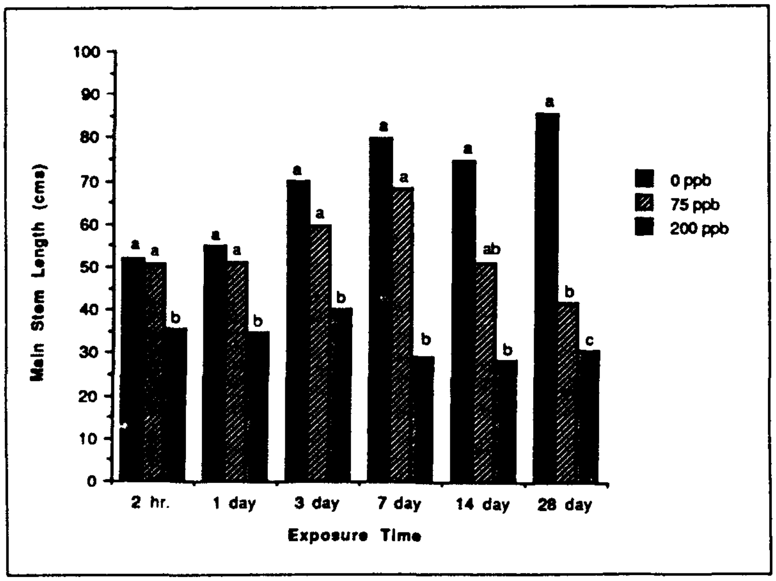


Figure 1. Average main stem length of Eurasian watermilfoil 4 weeks after exposure to flurprimidol for various periods of time. Data analyzed by ANOVA and Student-Newman-Keuls multiple range test

At 75 µg/L flurprimidol, significant reduction in main stem length (Figure 1) and plant weights was not noted until the plants had been exposed for 2 weeks.

Outdoor tank studies with flurprimidol and hydrilla. Main stem lengths were significantly reduced at both concentrations (75 and 750 µg/L) at all time intervals (Figure 2). In general, the treated plants were lying prostrate on the sediment surface, whereas the untreated plants were upright. This was demonstrated by comparing the number of stolons (lateral shoots lying horizontally on the sediment).

At 1- and 2-hr exposures, the number of stolons produced by plants treated with 750 µg/L was significantly greater than the number produced by plants at either 0 or 75 µg/L. After 24-hr and 3-day exposure times, plants treated at both 75 and 750 µg/L had significantly more stolons than did untreated plants. For example, at 3 days, the untreated plants had an average of one stolon, whereas plants treated with 75 and 750 µg/L had 2.5 and 5 stolons, respectively.

Although the morphology of the treated plants was quite different from the untreated plants, fresh and dry weights were not significantly different from those of untreated plants. Analyses (GC/MS) of flurprimidol residues in plant, sediment, and water samples are currently being conducted.

Laboratory bioassays. With long-term exposures of bensulfuron methyl, the main stem length of Eurasian watermilfoil was reduced by 15 percent after a 4-week exposure to 6 µg/L and by 42 percent at 60 µg/L, compared to untreated controls. No effects were observed at 0.6 µg/L. At

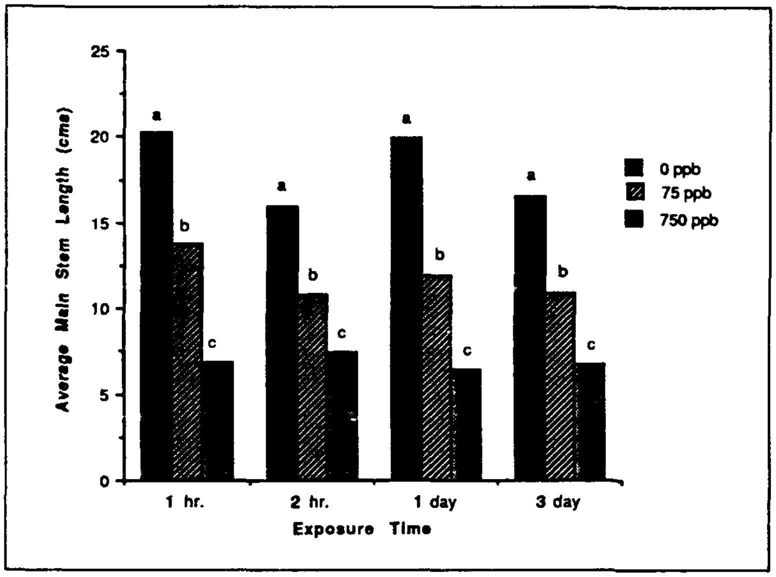


Figure 2. Average main stem length of hydrilla 5 weeks after exposure to flurprimidol for various periods of time. Data analyzed by ANOVA and Student-Newman-Keuls multiple range test

6 weeks, main stem lengths at 6 and 60 µg/L were 20 and 52 percent shorter, respectively, than untreated controls. A bushy growth form with many abnormal lateral branches was observed at 60 µg/L. Photosynthetic rates, however, were not significantly different from those of the untreated control.

At 8 weeks, main stem reduction was still observed with 33 percent reduction at 6 µg/L and 66 percent reduction at 60 µg/L. At 60 µg/L, the plants seemed brittle with many malformed side branches and no roots. However, photosynthesis was still normal, and buds that were removed and transferred to fresh, untreated medium sprouted normally after another 6 to 8 weeks. No growth reduction effects were observed at 0.6 µg/L.

In the duration-of-exposure experiment with bensulfuron methyl, no effect was observed after 2-hr exposures. After 12 hr, main stem lengths of treated plants were 29 percent of those of untreated plants at the end of the recovery period. Similar effects were noted at all intervals after 12 hr, with main stem lengths reduced in the treated plants. Another effect was a bushy appearance due to lateral stem proliferation. It appeared that the main stem apical tip turned pale and died, and that this stimulated the production of numerous lateral buds and shoots.

Results from the dose-response experiments suggest that the herbicides imazapyr, imazaquin, and imazethapyr have a greater potential to regulate the growth of Eurasian watermilfoil than of hydrilla (Table 1). For example, imazapyr was toxic to hydrilla (as indicated by reduction in photosynthetic rate) at the same concentration (25 µg/L) that it first showed growth reduction in main stem length. In contrast, there was approximately a 20-fold difference between the toxic dose and the minimum dose required to reduce main stem length in Eurasian watermilfoil. Imazaquin showed the greatest range between toxicity and stem length reduction in Eurasian watermilfoil.

Table 1
Concentration Range Tested, Minimum Effective Dose (ppb) to Cause Main Stem Length Reduction, and Minimum Effective Dose (ppb) to Cause Significant (at Least 10-fold) Reduction in Photosynthetic Rate

Treatment	Range	Main Stem Length Reduction	Reduction in Photosynthetic Rate	Factor[1]
Imazapyr				
Milfoil	5-500	5	100	20
Hydrilla	1-25	25	25	1
Imazaquin				
Milfoil	5-500	5	100-500	20-100
Hydrilla	5-100	10	100	10
Imazethapyr				
Milfoil	10-10,000	50	500	10
Hydrilla	5-100	10-25	100	4-10
Limit				
Milfoil	50-1,000	250	>1,000	>4
Hydrilla	10-1,000	50-100	500	5-10

[1] Ratio of the adverse-effect dose to length-reduction dose.

Hydrilla was more sensitive to amidochlor than was Eurasian watermilfoil, showing reduction in stem length at 50 to 100 µg/L (compared to 250 µg/L required for stem reduction in Eurasian watermilfoil). Hydrilla was also more sensitive in terms of toxicity, and was killed at 500 µg/L. The toxicity dose of amidochlor on Eurasian watermilfoil remains to be established; no toxicity was observed at the maximum concentration tested (1,000 µg/L).

Discussion

The outdoor tank studies confirm the earlier results, which indicated that growth reduction from gibberellin synthesis inhibitors, such as flurprimidol, can be achieved in hydrilla after very short exposure times. As shown in this year's study, exposure to 75 µg/L flurprimidol for only 1 hr effectively reduced main stem length, and a 24-hr treatment promoted stolon formation and prostrate growth. Based on these and previous years' data, the weight of the hydrilla does not appear to differ between treated and untreated plants. This indicates that the same amount of biomass in treated plants is produced as in untreated plants, but in a more compact form.

The Eurasian watermilfoil results also confirm previous years' experiments in which flurprimidol concentrations of 75 µg/L or less did not result in significant main stem reduction unless exposed for longer periods (2 weeks). Our results suggest that higher concentrations (e.g., 200 µg/L) will be required if short exposure times are necessary (such as in flowing water).

Of the compounds tested in the laboratory bioassay, bensulfuron methyl, amidochlor, and possibly imazaquin have the greatest potential as growth regulators, particularly on Eurasian watermilfoil. Bensulfuron methyl seems to be relatively nontoxic, yet reduces main stem heights for long exposures of up to 8 weeks at a range of 6 to 60 µg/L. No effect was noted at 0.6 µg/L. At least a 12-hr exposure to 60 µg/L appeared to be required for long-term stem length reduction.

In contrast to the herbicidal compounds, which generally result in plants that are stunted (i.e., the stem apex ceases growth), amidochlor produced effects that resemble those of the gibberellin synthesis inhibitors (stem apex continued to grow but internode length was decreased). Higher concentrations of amidochlor are required for a stem reduction effect; however, little toxicity is shown at concentrations as high as 1,000 µg/L on Eurasian watermilfoil. Further work with imazaquin and amidochlor is warranted.

Evaluation of Bensulfuron Methyl on Hydrilla (USDA Aquatic Plant Management Laboratory)

Materials and methods

Monoecious and dioecious hydrilla used in this study were obtained from stock cultures grown over a period of several months in outdoor aquaria in Fort Lauderdale, FL. The monoecious hydrilla was established from tubers collected from the Potomac River, Virginia. Dioecious hydrilla was established from stem apexes collected from Rodeo Lake in Davie, FL.

The investigation was conducted in outdoor tanks located on the grounds of the Fort Lauderdale Research and Education Center, University of Florida, in Fort Lauderdale. Tanks were 0.8 m wide by 2.2 m long (1.7×10^{-4} ha) and were filled with pond water to a maximum depth of 0.6 m. Pond water was from the same source as described previously (Van and Steward 1986).

Uniform low water pressure was maintained by constant overflow in a standpipe, and flow to individual tanks was regulated by small petcock valves to provide one water volume change every 24 hr. A system of 36 tanks (arranged in three rows of 12 tanks) was used. Chemical treatments (concentration × exposure) were arranged as a 4 × 3 factorial with three replicates, and were assigned to the tanks in a randomized block design.

Hydrilla tubers were allowed to germinate in pond water at 25° C under continuous light for 5 weeks before planting. Ten sprouted tubers, 10 cm long, were planted in plastic pots (25-cm diameter, 20 cm deep). The pots were filled with a rooting medium consisting of approximately 12 kg of sandy loam (60 percent sand, 26 percent silt, 14 percent clay) enriched with 10 g of a slow-release fertilizer.[1]

Four pots of each hydrilla biotype were placed in each tank, and the plants were allowed to grow for 2 weeks prior to chemical treatment. On 1 August 1990, bensulfuron methyl was applied to the tanks at concentrations of 0, 0.05, 0.10, and 0.20 mg/L. Plants were in contact with each of the four treatment concentrations for 3, 7, and 14 days. Water exchange was halted for the length of the designated exposure time, after which the tanks were flushed three times and the water exchange resumed.

One pot of each plant biotype from each tank was harvested at 1, 2, 4, and 6 months after chemical treatment. Harvested biomass was partitioned, numbers of tubers counted, and dry weights determined. Data were subjected to analysis of variance (ANOVA) using a split-split plot design with herbicide treatments as main plots, hydrilla biotypes as subplots, and harvest dates as subplots. In this report, only data on the 1- and 2-month harvests are reported.

Results

Response of monoecious hydrilla 1 month after the bensulfuron methyl treatments is illustrated in Figure 3. Exposure for 3 days at 0.05 mg/L resulted in an approximate 35-percent reduction of plant biomass in monoecious hydrilla. Increasing bensulfuron methyl concentrations to 0.20 mg/L still provided only marginal control when chemical exposure was limited to 3 days. When exposure to the chemical was extended to 7 days, the 0.05 mg/L bensulfuron methyl treatment provided approximately 70 percent reduction of plant biomass. However, complete inhibition of both plant growth and tuber production in monoecious hydrilla required a 14-day exposure to concentrations of 0.05 mg/L bensulfuron methyl.

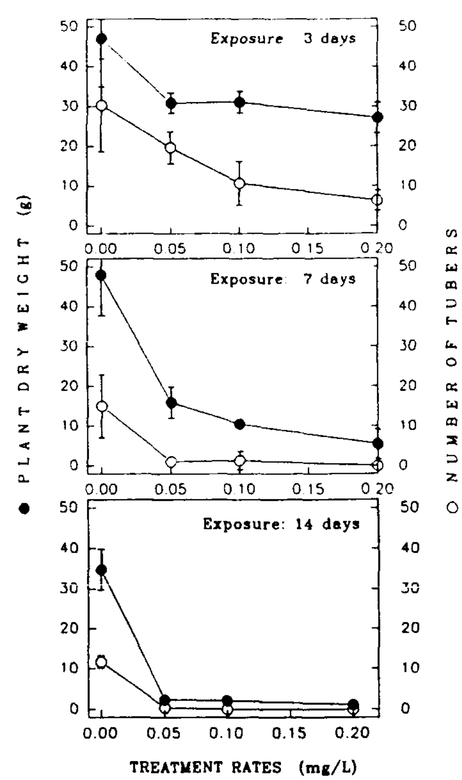


Figure 3. Effects of bensulfuron methyl on growth and tuber production in monoecious hydrilla 1 month after treatment. Values are means and standard deviations for three replicates

Regrowth began within 2 months in monoecious hydrilla, as evidenced by increases in plant weight in the second harvest (Figure 4). Plants recovered almost completely at all treatment concentrations when exposure to bensulfuron methyl was limited to 3 or 7 days. Inhibition of tuber production persisted after 2 months, even in treatments where plants had recovered from the initial herbicidal

[1] Sierra (17-6-10) formulated for an 8- to 9-month release rate (Sierra Chemical Company).

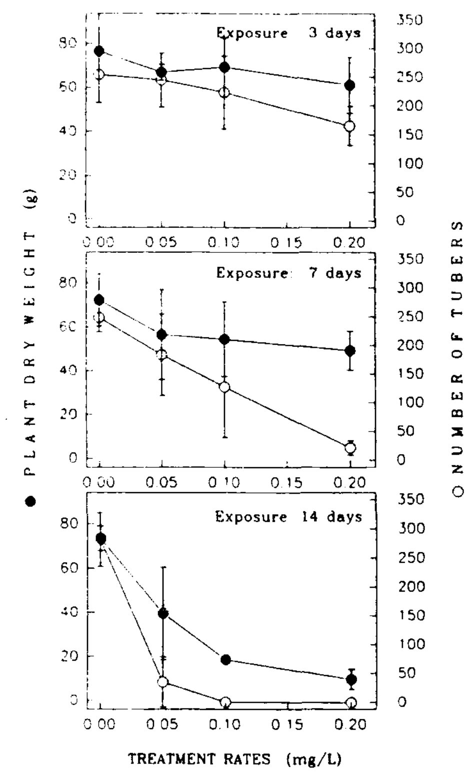


Figure 4. Effects of bensulfuron methyl on growth and tuber production in monoecious hydrilla 2 months after treatment. Values are means and standard deviations for three replicates

effects of bensulfuron methyl. After 2 months, untreated control plants produced an average of 281 tubers per pot, while no tubers were found with plants treated with 0.10 mg/L bensulfuron methyl for a 14-day exposure.

Similar results were obtained with dioecious hydrilla (Figures 5 and 6). The highest concentration of bensulfuron methyl (0.20 mg/L) and longest exposure time (14 days) were required to maintain adequate control of plant biomass after 2 months. Previous studies showed that dioecious hydrilla grown from tubers begins to produce new tubers after about 8 weeks (Van 1989). In this study, untreated control plants produced an average of 3 to 10 tubers per pot by the second harvest after 2 months (Figure 6), while tubers were still lacking in all plants that had been exposed to bensulfuron methyl for 14 days.

Discussion

Bensulfuron methyl reduced plant growth in both monoecious and dioecious hydrilla at the lowest concentration tested, confirming an earlier report by Anderson and Dechoretz (1988). These authors also reported that effective control of monoecious hydrilla required 7 days of exposure to 0.025 to 0.05 mg/L bensulfuron methyl.

Our results generally indicate that a longer exposure time (minimum of 14 days) and

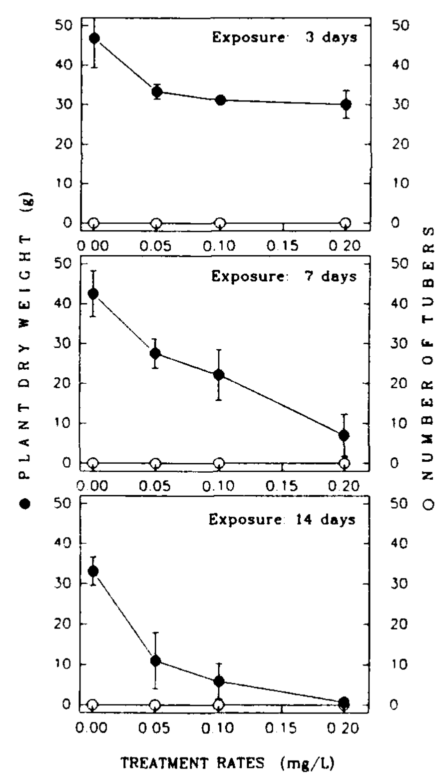


Figure 5. Effects of bensulfuron methyl on growth and tuber production in dioecious hydrilla 1 month after treatment. Values are means and standard deviations for three replicates

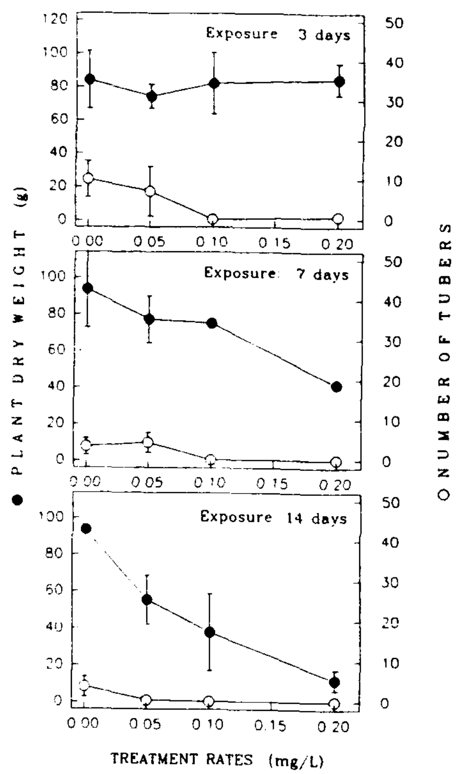


Figure 6. Effects of bensulfuron methyl on growth and tuber production in dioecious hydrilla 2 months after treatment. Values are means and standard deviations for three replicates

higher rates of bensulfuron methyl (0.10 to 0.20 mg/L) are needed to achieve hydrilla control under Florida conditions. Heavy regrowth was observed after 2 months in both hydrilla biotypes when exposure to bensulfuron methyl was limited to less than 7 days.

Bensulfuron methyl also suppressed tuber formation in monoecious hydrilla at all concentrations tested. The suppression level of tuber formation was often much greater than the corresponding reduction of plant biomass exhibited by the same bensulfuron methyl treatment, suggesting that the inhibition of tuber formation was probably independent from a general retardation of plant growth. Furthermore, the growth-regulating effect of tuber inhibition persisted long after the plants had recovered from the initial herbicidal effects.

Future harvests will be made after 4 and 6 months in an attempt to determine the length of time hydrilla tuber formation remains suppressed by the various bensulfuron methyl treatments.

Evaluation of Bensulfuron Methyl on Eurasian Watermilfoil (Waterways Experiment Station)

Materials and methods

The experiment was conducted in an aquarium system located in a controlled-environment greenhouse, using a slightly modified procedure previously described by Green (1988). The system consisted of twenty-four 55-L aquariums (0.75 m × 0.3 m^2), each independently supplied with a continuous flow of reconstituted hard water (Smart and Barko 1984). This allowed the total water volume (50 L) of each aquarium to be exchanged every 24 hr.

Air was bubbled through each aquarium as a source of carbon dioxide and for water circulation. Water temperature was maintained at $25^{\circ} \pm 2^{\circ}$ C throughout the experiment. Overhead supplemental lighting provided a light:dark cycle of 13:11 hr. The mean photosynthetically active radiation measured at the water surface was 450 $\mu E/m^2$.

Eurasian watermilfoil used in this study was supplied by the Lewisville Aquatic Ecosystem Research Facility in Lewisville, TX. Watermilfoil was separated into 10-cm apical segments and planted 5 cm deep into sediment-filled beakers. The sediment used was collected from Brown's Lake at the Waterways Experiment Station, and was amended with nutrients (Ra-pid-gro) to avoid any possible nutrient limitations.

Eleven beakers were placed in each aquarium, and plant segments were allowed to grow to establish new shoot and root growth. When adequate root growth was established (approximately 2 weeks), plants were trimmed back to a height of 16 cm; 1 week

thereafter, chemical treatments were applied. One beaker of plants was randomly removed from each aquarium immediately prior to treatment to provide an estimate of treated biomass.

Established plants were exposed to static (flow-through water system turned off) treatments of varying bensulfuron methyl concentrations for 7- and 14-day time periods (Table 2). Following the exposure time period, the aquariums were drained and rinsed three times to remove chemical-treated water, after which the continuous flow-through water system was resumed for the duration of the experiment.

Table 2
Treatment Rates and Exposure Time Periods

Rate of Bensulfuron Methyl (µg/L or ppb)	Exposure Time (days)
0 (control)	0
5.0	7
25.0	7
37.0	7
50.0	7
100.0	7
25.0	14
50.0	14

Treatments were arranged in a completely randomized design with three replicates. Visual ratings of plant injury were recorded weekly. At the conclusion of the experiment (6 weeks posttreatment), root and shoot biomass were measured for each treatment. Data were analyzed using ANOVA, and treatment effects were separated using the Duncan Multiple Range Test.

Results

All treatments significantly reduced shoot biomass (Figure 7). Higher concentrations and longer exposure periods were most effective. Biomass reductions ranged from 39 to 86 percent when compared to the untreated controls, with the most effective treatment

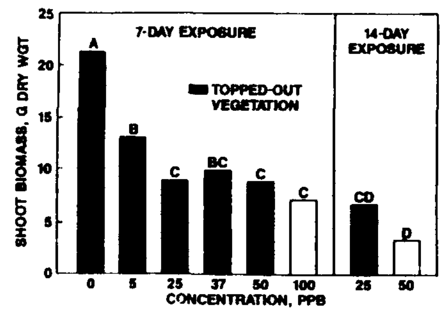


Figure 7. Effects of bensulfuron methyl on shoot biomass of Eurasian watermilfoil 6 weeks after treatment. Data are means of three observations. Letters denote significant differences at P = 0.05

being a 14-day exposure to 50.0 µg/L bensulfuron methyl. Regrowth was observed on all treatments by the end of the experiment, and the plants had "topped out" or grown to the water surface in all but two treatments.

Effects of bensulfuron methyl on root growth were similar to those on shoots (Figure 8). Root biomass was significantly reduced by all treatments and appeared to be concentration dependent. Treatments of 50.0 µg/L at 14-day exposure showed the greatest root growth inhibition.

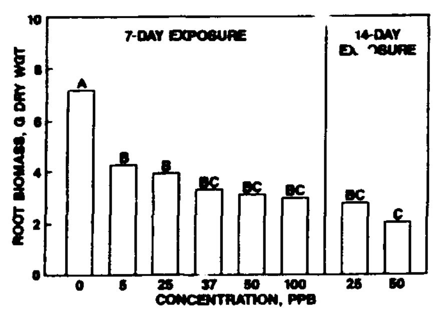


Figure 8. Effects of bensulfuron methyl on root biomass of Eurasian watermilfoil 6 weeks after treatment. Data are means of three observations. Letters denote significant differences at P = 0.05

Discussion

Results indicate that bensulfuron methyl is effective at reducing the growth of Eurasian watermilfoil. Shoot and root growth were significantly inhibited at very low concentrations (5.0 µg/L). As evidenced by the occurrence of regrowth, longer exposure periods and higher concentrations seem to be necessary to maintain adequate growth suppression. Studies by Anderson and Dechoretz (1988) also reported reduced shoot and root biomass of Eurasian watermilfoil when exposed to low concentrations of bensulfuron methyl.

Future Research

In conclusion, future plans for this work unit include the following.

- Continue evaluation of bensulfuron methyl on both hydrilla and Eurasian watermilfoil. Results thus far indicate that longer exposure periods or contact times are needed for adequate growth suppression of both plant species.

- Complete studies at Purdue University identifying the persistence of these products, namely the gibberellin synthesis inhibitors, in soil, water, and plant tissues. Results will provide critical information for registration purposes.

References

Anderson, L. W. J., and Dechoretz, N. 1988. Bensulfuron methyl: A new aquatic herbicide. Pages 224-235 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Green, W. R. 1988. Herbicide concentration/exposure time studies of Eurasian watermilfoil. Pages 205-212 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lembi, Carole A., and Netherland, Michael D. 1989. Bioassay of plant growth regulator activity on aquatic plants. Pages 118-127 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Smart, R. M., and Barko, J. W. 1984. Culture methodology for experimental investigation involving rooted submersed aquatic plants. Miscellaneous Paper A-84-6. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van, T. K. 1989. Differential responses to photoperiods in monoecious and dioecious *Hydrilla verticillata. Weed Science* 37:552-556.

Van, T. K., and Steward, K. K. 1986. The use of controlled-release fluridone fibers for control of hydrilla (*Hydrilla verticillata*). *Weed Science* 34:70-76.

Phenology of Aquatic Plants

by
John D. Madsen[1]

Introduction

Phenology is the study of natural phenomena that recur periodically (such as blossoming, fruit set, germination, and senescence) and their relationship to climate and changes in environment. When applied to aquatic plants, we are examining the modification in timing or expression of the life cycle of plants resulting from variations in climate or conditions. The characteristics examined are not only those visual characteristics normally considered, but also the physiological changes in plants that accompany the more evident life stages. Although this sounds basic, a better understanding of phenology of plants has significant implications to the application of all control technologies.

The objectives of this research are to:

- Define seasonal trends in growth, allocation, and vegetative or sexual propagation and spread of target species.
- Define "weak points" in the life cycles of target species for the application of control tactics, either singly or in concert.
- Integrate phenology of target species to the life histories of biocontrol agents.

By design, this research effort will seek to coordinate activities with other work units within the Aquatic Plant Control Research Program to achieve these objectives. In particular, cooperation is sought with the Simulation and Biocontrol efforts to identify information needs for directing further data collection.

Significant contributions have already been made in this effort, particularly in studies of waterhyacinth (*Eichhornia crassipes* L.) at both the WES and the Lewisville Aquatic Ecosystem Research Facility (LAERF).[2,3] Current research at the LAERF will be reviewed, and future directions and target species discussed.

Current Research

Experimental approach

Research on waterhyacinth was performed at the LAERF using separate 0.4-ha ponds. Components of the research effort included (1) growth, biomass, and resource allocation, (2) production estimates through leaf tag studies, and (3) sexual propagation studies.

Growth, biomass, and resource allocation

Seasonal biomass, growth rates, and allocation of biomass, carbohydrates, and nutrients

---

[1] US Army Engineer Waterways Experiment Station, Lewisville Aquatic Ecosystem Research Facility, Lewisville, TX.

[2] K. T. Luu and K. D. Getsinger. 1990. Coordination of control tactics with phenological events of aquatic plants. Pages 123-127 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

[3] K. T. Luu and K. D. Getsinger. 1990. Seasonal biomass and carbohydrate distribution in waterhyacinth: Small-scale evaluation. Technical Report A-90-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

were studied in 1990 by planting sets of 1-m^2 floating rings in groups (or cohorts) initiated at different times throughout the growing season. Two ponds were also used in this experiment: one to which no treatments were added (control) and one to which nitrogen fertilizer was added each week (nitrogen-added). Initially, only 2.5 kg was added weekly but, by mid-July, 10 kg of nitrogen was added each week. Table 1 indicates the dates cohorts were initiated and the subsequent sampling schedule.

Table 1
Sampling Schedule for Ring Study Determining Growth, Biomass, and Resource Allocation[1]

Week of	Cohort A	Cohort B	Cohort C
5 Jun 90	0		
12 Jun 90	1		
19 Jun 90	2		
26 Jun 90	3		
3 Jul 90			
10 Jul 90	5		
17 Jul 90			
24 Jul 90	7	0	
31 Jul 90		1	
7 Aug 90	9	2	
14 Aug 90		3	
21 Aug 90			
28 Aug 90	12	5	
4 Sep 90			0
11 Sep 90		7	1
18 Sep 90	15		2
25 Sep 90		9	3
2 Oct 90			
9 Oct 90	18		5
16 Oct 90		12	
23 Oct 90			7
3^ Oct 90	21		
6 Nov 90			
13 Nov 90		16	10
20 Nov 90	24		
27 Nov 90			
3 Dec 90		19	13

[1] Column entries indicate the number of weeks from cohort initiation when the samples were taken; week "0" indicates beginning of cohort and first sample.

On each sampling date, three rings from each pond were sampled as replicates. Until plants grew to cover the entire ring, all plants were harvested. Once plants covered the surface of the ring, a 0.25-m^2 quadrat was harvested from the center of the ring.

The plants were separated into roots, mature leaf laminae and petioles, young leaf laminae and petioles, stem bases, stolons, young plants, inflorescences, and dead material. These components were dried at 55° C, weighed, and ground for future analysis of carbohydrate and nitrogen content. Standard water quality parameters were measured weekly on the ponds, and water samples were taken for future analysis of major nutrients.

Production

Waterhyacinth production was examined by leaf tag studies. An individual mature rosette was placed in each of six rings (replicates) in each of two ponds (control and nitrogen-added) as in the ring study, with three cohorts started at separate times as above. These rosettes were examined each week, with all tagged leaves, inflorescences, and daughter plants counted. The untagged leaves, inflorescences, and daughter plants were also counted and tagged with small electric cable ties.

In addition, rosettes that were produced by, or attached to, tagged daughters or were free floating within the ring were also counted weekly. These data were then used to calculate weekly densities and production and loss rates of leaves, rosettes, and inflorescences.

Sexual propagation

The aspect of sexual propagation examined in 1990 was seedling survival. Waterhyacinth seedlings began to germinate in early July in two ponds at the LAERF that had been used the previous year to grow waterhyacinth. A hard 2-week freeze in 1989 ensured that none of these plants were able to overwinter vegetatively; all plants encountered were seedlings.

In one pond (No. 42), seedlings were found sprouting on damp marshy sediment. At this location, no plants floated due to lack of standing water. In addition, individual plants were tagged to follow the recruitment and mortality of individual seedlings. In the

other pond (No. 19), seedlings were germinating in 0.3 to 1 m of water depth. Therefore, the time to floating stage could be followed, but it was not possible to tag individual seedlings.

Seedlings in each pond were counted within enclosures weekly, and the number of flowering seedlings was examined.

Results and Discussion

Growth, biomass, and resource allocation

Resource allocation and growth rate data will not be presented pending further analysis. Cohort A failed to thrive, in part due to the poor condition of rosettes from the greenhouse. Subsequent growth from other cohorts indicated the importance of using robust plants from an outdoor culture pond. Density and biomass data for cohorts B and C will be discussed.

The density of mature and daughter plants was similar between the two ponds (control and nitrogen-added) for cohort B, but densities of both plant types were substantially higher in the nitrogen-added pond for cohort C (Figure 1). The decrease in density of both mature and daughter plants for the last sampling date of cohort C in the nitrogen-added pond may be due to intraspecific competition and self-thinning.

Biomass of cohort B was significantly higher in the nitrogen-added pond than the control pond, despite the similarity in density (Figure 2). This is evidence that increased fertility may well increase the growth rate or size of individual plants or leaves, rather than only increasing numbers of plants. Biomass data for cohort C have not yet been analyzed.

Production

Although other parameters were measured in the leaf tag study, only rosette number will be discussed (Figure 3). For cohort A, growth in both ponds was delayed for over 6 weeks. In June, the only plants available were in poor shape and were not acclimated to outdoor light. These plants required a long time to gain sufficient vigor to produce daughter plants. After this, the number of rosettes produced was significantly greater in the nitrogen-added pond than in the control pond.

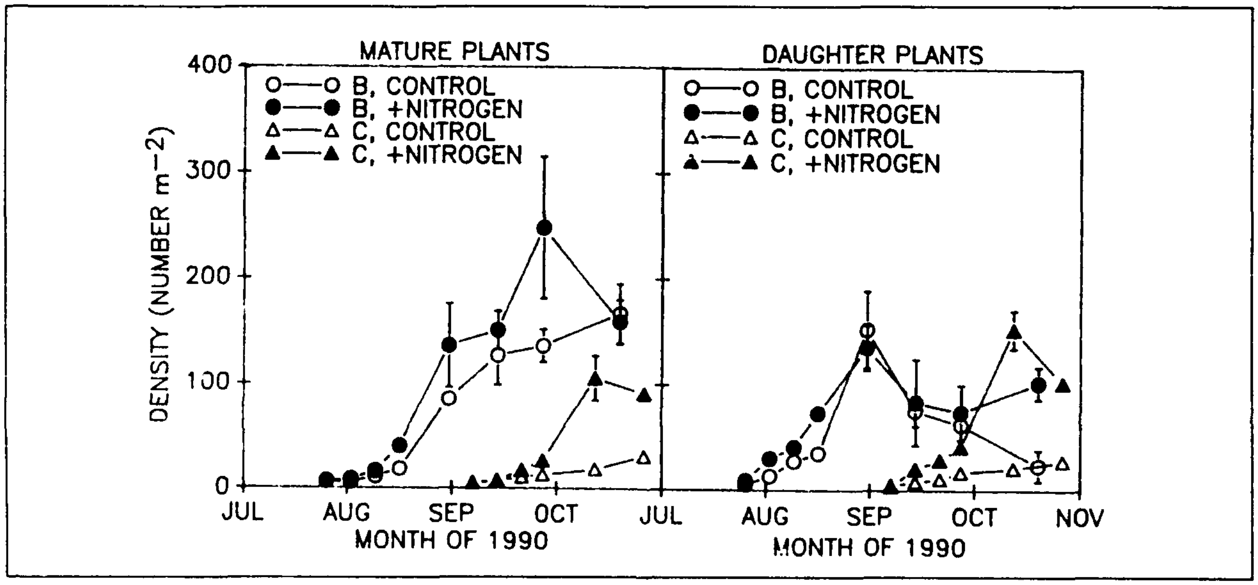


Figure 1. Density of waterhyacinth, by sampling date, in ring study for cohorts B and C in the control and nitrogen-added ponds

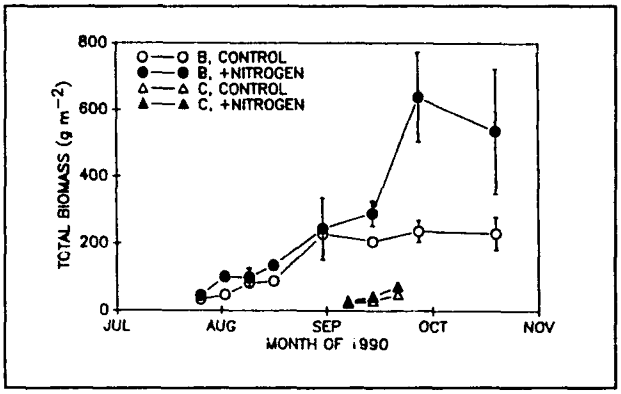


Figure 2. Biomass of waterhyacinth by sampling date in ring study for cohorts B and C in the control and nitrogen-added ponds

For cohort B, there was no apparent difference in the numbers of rosettes until early October, at which time the control pond exhibited a higher mortality rate than the nitrogen-added pond, which appeared to have a stable population size.

Rosette production rates in cohort C for the nitrogen-added pond were markedly higher than the control pond, higher than any other cohort. Therefore, it appears that increased fertility does increase rosette formation and maintenance.

Sexual propagation

Seedlings were first observed in the two ponds in mid-July, and the study enclosures were constructed the following week. Since seedling emergence was largely synchronous in both ponds, and most seedlings appeared to germinate in a 3-week period, germination may well have been triggered by an environmental factor such as water temperature or day length. However, a series of drawdowns or drying periods may also have been a factor in seed germination.

In pond 19, seeds germinated in 0.3 to 1 m of water depth. Development proceeded for 2 to 4 weeks, until seedlings were sufficiently mature to be positively buoyant, floating to the top (Figure 4). Seedling mortality was higher in pond 19 than in pond 42, due in part to fluctuating water levels that tended to strand young plants on emergent vegetation, where they then dried out.

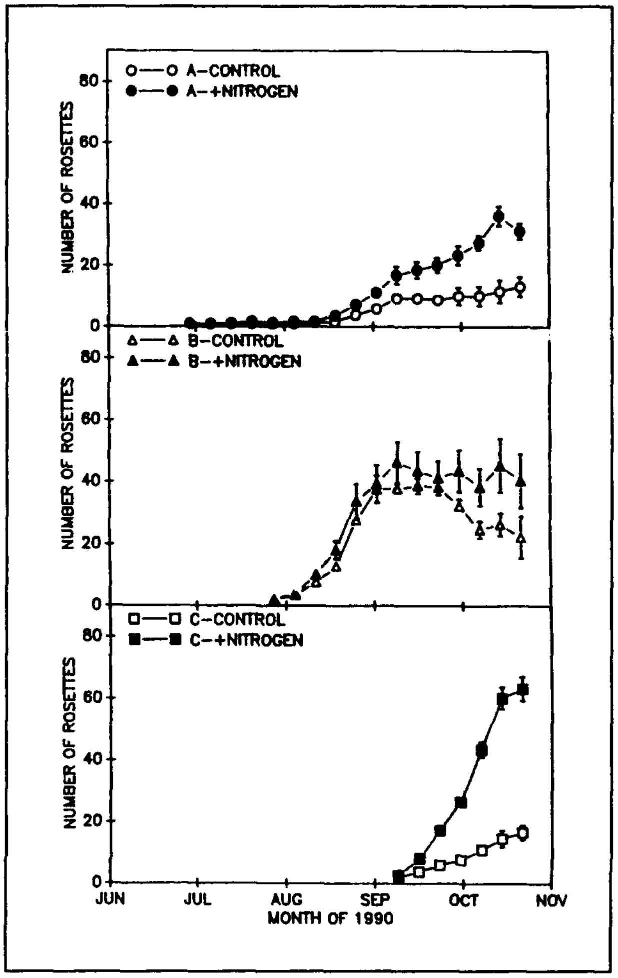


Figure 3. Number of rosettes resulting from one initial plant, by sampling date, in leaf tag study for cohorts A, B, and C in the control and nitrogen-added ponds

Growth and maturation of seedlings in pond 19 was slower than in pond 42, with plants reaching maturation and flowering after at least 13 weeks (90 days), with peak flowering at 14 weeks (100 days). Seedlings in pond 19 that reached flowering were those that had managed to establish on the sloped shoreline.

In pond 42, seedlings germinated and grew on a wet organic sediment. In general, these plants grew faster and produced more daughters. Mortality was very low (Figure 4). Also,

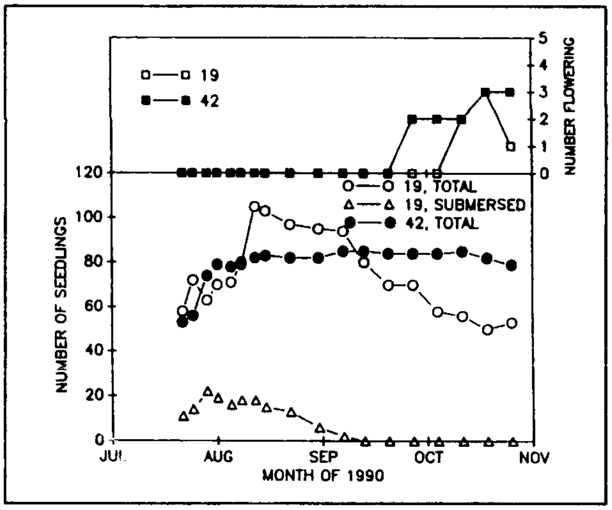


Figure 4. Number of flowering seedlings (top) and number of seedlings (bottom), by sampling date, for all seedling enclosures in ponds 19 and 42

compared with pond 19, more plants reached flowering stage and flowered earlier (10 weeks, 70 days). Mature seed pods holding seeds were also noted.

The implications of seed germination and survival to efficient management of the plant are several and significant.

First, it is possible for waterhyacinth to survive from one year to the next by an annual life cycle. Waterhyacinth could recover from occasional hard winters (such as experienced in 1989) from the seed bank alone, though population densities would initially be lower than if vegetative perennation had occurred. The northern range of waterhyacinth should then be delimited by the locations in which it can germinate and grow to flowering stage within a given growing season.

Second, waterhyacinth can recover in some localities from herbicide treatment or drawdowns, or other control techniques, by seed germination. Population reestablishment rates would be slow, but this does indicate the need to monitor sites after management tactics are applied to prevent regrowth.

Last, it is possible for waterhyacinth to be dispersed by seed, without any vegetative propagules being transported.

Future Research

Phenological studies should be performed on all major nuisance species to better implement control strategies. Current plans for the future will focus on waterhyacinth, Eurasian watermilfoil (*Myriophyllum spicatum* L.), and hydrilla (*Hydrilla verticillata* (L.f.) Royle).

Waterhyacinth

Growth, biomass and resource allocation studies, leaf-tag studies, and sexual propagation studies as outlined above will continue in fiscal year (FY) 1991. In addition, regular measurements of field net photosynthesis and respiration of leaves, and respiration of stem bases and roots, will be obtained to provide better data for modeling purposes. Additional studies of sexual production are planned, including examination of the environmental requirements for seed germination and seedling survival, as well as studies of seasonal flowering trends.

Eurasian watermilfoil and hydrilla

Growth, biomass, and resource allocation studies, seasonal photosynthesis and respiration measurements, and seasonal trends in vegetative and sexual propagation are planned for both Eurasian watermilfoil and hydrilla. Propagation and spread of these species will be emphasized in some of the seasonal studies planned, as well as contrasting the efficiency of the various vegetative and sexual modes of propagation of the two species, including both monoecious and dioecious hydrilla.

Plans are to initiate studies on Eurasian watermilfoil in FY 91, with hydrilla to follow in the near future. In addition to studies at the LAERF, cooperative efforts at other localities

will help to establish the geographic variability in phenological phenomena and expand the range of phenological topics examined.

Conclusions

Phenology studies will create a better understanding of the basic life cycle and biology of target species, providing insight to the key points at which various management tactics can be implemented. This work unit is interactive; it requires input from many other work units, and in return provides data to them.

In the future, the Phenology work unit will examine geographical variation in target species' responses and growth, and the effectiveness of various important control tactics.

Acknowledgments

The author would like to thank G. Dick, K. Getsinger, and R. M. Smart for interaction and assistance in experimental design development and implementation, and R. Westover for technical assistance.

Industry Overview: The Future of Herbicides

by
Francis T. Lichtner[1]

To look to the future of herbicides and herbicide discovery, we must understand the forces that shape industry research (Figure 1). Historically, market need, project/product economics, and competitors' offerings have primarily determined aquatic plant control targets. Once these targets were defined, chemicals were discovered to successfully meet those needs. However, in the past few years and continuing into the future, evaluation of the environmental impact of products and consideration of the public perception of the risks and benefits of crop protection chemicals have resulted in redefinition of the discovery process.

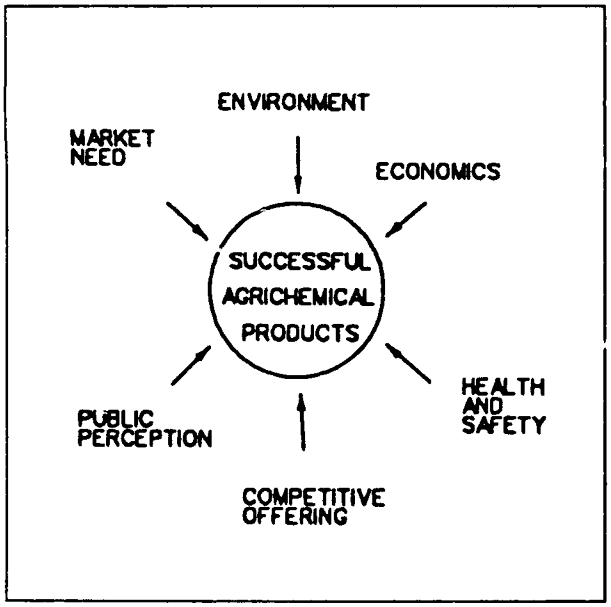


Figure 1. Forces shaping agricultural chemical research

The objectives of this presentation are to examine the forces that shape industry research and to discuss how Du Pont approaches herbicide discovery. In many respects, this approach is applicable to the agricultural chemical industry as a whole.

Due to the time lag between product discovery and commercialization, industry researchers attempt to anticipate the future marketplace. We estimate that the demand for food (and water) will increase at an annual rate of 1 to 2 percent. Although the pesticide business is mature, companies will capture revenues by providing superior replacements to those products already on the market. Environmental and safety concerns for current products and practices will create opportunities for new replacement products and services.

To satisfy these needs, traditional crop protection chemicals (CPCs) as well as novel chemical and biological solutions (including the use of molecular biology and genetic techniques) will be sought. In addition, continued consolidation of companies will occur in the agricultural chemical industry, as greater sales volumes are needed to provide critical revenues for research, development, and stewardship of these new products and services.

There is little doubt that the products of the future will appear different than those of the present and past (Table 1). Herbicides have evolved from the high-use rate inorganic compounds, through the hormonals, toward the current single-target, low use-rate technology. Similar trends are also seen in the fungicide and insecticide areas. CPCs of the future will look as different from current products as the sulfonylureas do to the ureas and triazines.

[1] Du Pont Agricultural Products, Newark, DE.

Table 1
Evolution of Agricultural Chemicals

Year	Herbicide	Insecticide	Fungicide
1920		Inorganics	
1930	Phenoxy	DDT	
1940		Phosphate	
1950	Triazine	Organochlorine	Carbamate
1960	Carbamate Urea Amide DNA	Carbamate	Benzimidazole
1970	Glyphosate		Triazole
1980	Sulphonylurea Imidazolinone	Pyrethroid	
1990	?	?	?

This era of new product technology will also be much costlier from a discovery and development standpoint (Figure 2). Today, an average of over 40,000 compounds must be tested to discover a new product. Once that product is identified, over $40 million and 8 years of development/registration processes are required to bring the product into the marketplace (Figure 3).

These figures do not take into consideration the capital investment needed to construct research and manufacturing facilities, nor the costs involved in maintaining the product in the marketplace. Under these circumstances, it is increasingly difficult and costly to rely on traditional discovery (or screening) programs to satisfy the demand for new products. As a result, traditional whole-plant iterative chemical-biological optimization processes have been coupled with new in vitro testing programs, specific target-site characterization/inhibitor design teams, molecular modeling activities, and special tests to identify novel, low-level leads.

Control of nuisance aquatic plants offers special challenges for the discovery of new control technologies. Our often-limited water resources must serve many diverse "customers," including those using water for agriculture, drinking, recreation, or habitat. These multiple uses demand vegetation management rather than complete, indiscriminate control of all plant life. As a result, aquatic plant control must rely on an integrated systems approach.

Already, the marriage of biological and chemical technologies is impressive, and this trend will clearly continue. However, market opportunities for aquatic herbicides are not fully or readily defined; this situation makes it doubtful that industry will design large programs for aquatics alone. Most likely, companies will seek to extend registrations of

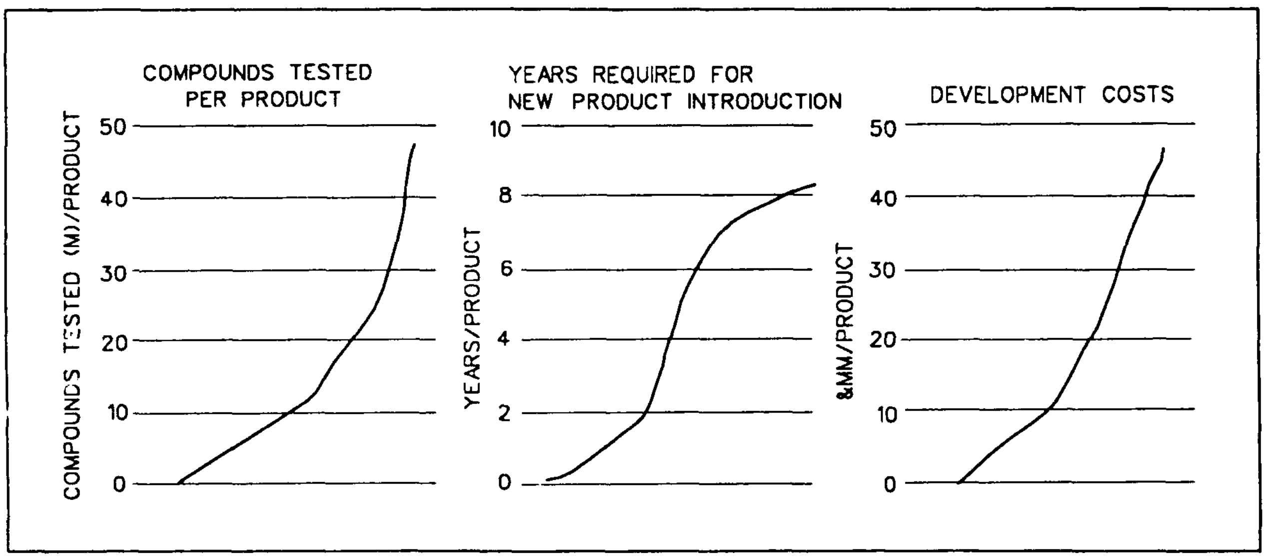


Figure 2. Trends in compounds tested and time and cost associated with research and development of agricultural chemicals

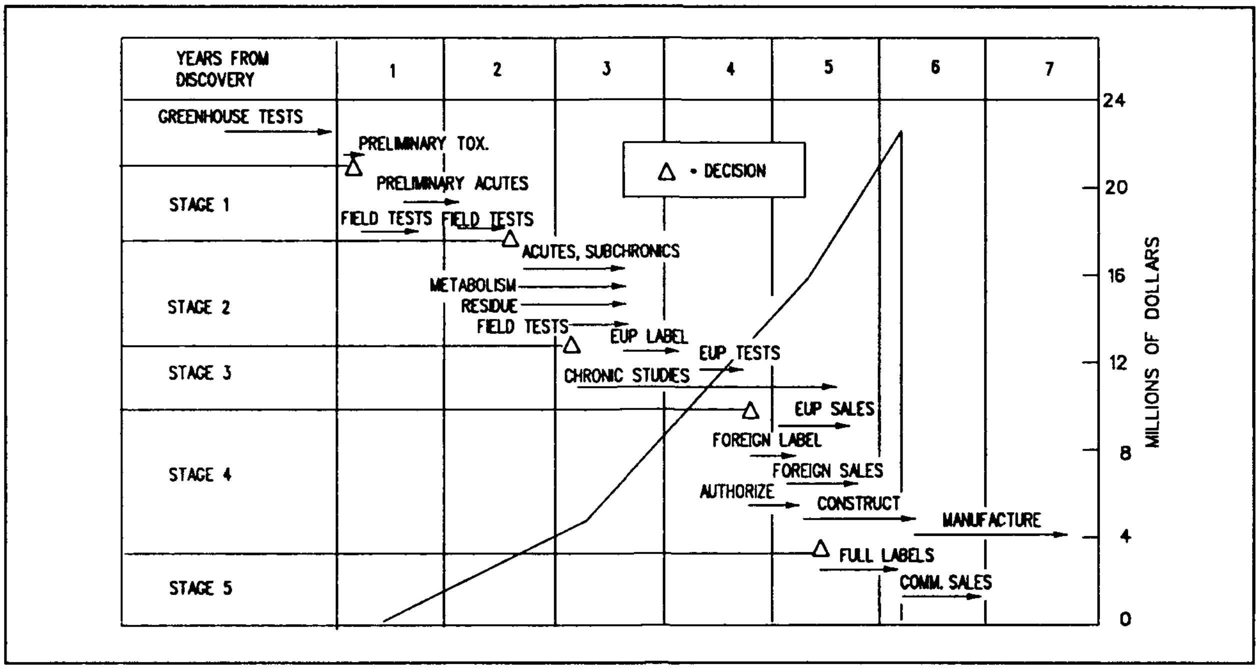


Figure 3. Partial costs (cumulative) and time required for commercialization of a crop protection chemical

suitable older products, and new candidates, to aquatic sites.

To best serve the unique needs of aquatic plant control, we will require novel formulations of these products, and new application techniques to deliver and restrict these chemical and biological agents to the target plants.

Certain beliefs drive our approach to designing discovery research processes and organizational structure. These beliefs can be summarized as follows:

- Pest control technology will continue to be essential for meeting worldwide food needs.
- Public concerns and regulatory pressures will continue to increase.
- Alternative genetic and biological methods for pest control will become increasingly important.
- Major opportunities exist for safer, more effective products.

In particular, we in Du Pont place great emphasis on discovering safer products for the marketplace. Potential new products must have certain characteristics (investigated very early in the discovery process), to ensure that minimal investment occurs for those candidates that do not meet the appropriate criteria. These criteria include: (1) quick degradation or breakdown, (2) negligible risk to humans and wildlife, (3) little or no residue, (4) no adverse effect on water quality, (5) minimization of active ingredient, (6) target specificity, and (7) no harm to beneficial insects.

While these additional testing requirements add time and cost to the discovery process, they permit us to understand more fully how compounds interact with the environment. This increased understanding also allows us to move toward our vision, that of a growing partnership with nature. The chemical industry shares society's value for environmental integrity, and it knows that science-based solutions to society's problems will add positively to the overall quality of life.

Future of Chemical Technology in Aquatic Plant Management Operations[1]

by
Joseph C. Joyce[2]

Introduction

In order to look at the future of chemical aquatic plant operations, one must focus upon the political, social, and scientific environment in which the aquatic plant manager must operate. The aquatic plant manager functions in what should be considered our most precious natural resource—water. The public attention and concern over pesticide-related issues, particularly with regard to water, is being strongly reflected in institutional controls that determine how herbicides or plant growth-regulating compounds are currently used and will be used in the future.

Probably no other publication has had a more profound effect on the products the aquatic plant management industry has at its disposal than Rachel Carson's *Silent Spring*, which was first published in 1962. Twenty eight years later, the majority of the public's perception of pesticides in general is still molded by the concepts and thoughts expressed by Ms. Carson. If our use of herbicides in aquatic plant management will be influenced by public opinions and pressures, a look at *Silent Spring* and the objectionable characteristics of pesticides, and the manner in which they were used, seems appropriate. If the concerns expressed in *Silent Spring* can be addressed, the aquatic plant manager will retain the use of safe, environmentally compatible compounds as part of aquatic plant management programs. It is on this basic premise that the following analysis of aquatic herbicides and their future use was undertaken.

Characteristics of Aquatic Herbicides

Are the herbicides that currently receive widespread use in aquatics of such a nature that they would be subject to the criticisms raised by Ms. Carson? Table 1 lists the 20 compounds that were available for use in and around aquatic sites in 1976 (Anonymous 1976) and the nine that are available today. Thirteen of the compounds available in 1976 are no longer in use in aquatics, and two new ones have been added. The reasons the 13 compounds are no longer used in aquatics vary. Some of them are no longer used because of:

- Failure to meet the new registration requirements of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) or cancellation because of concerns raised under FIFRA-related reviews, such as toxicity, carcinogenicity, biomagnification, or environmental fate.
- Loss of market share through competition.
- Development of new alternate compounds or control techniques.
- Expiration of patent.
- Corporate unwillingness or inability to support additional data requirements for financial or other reasons.

---

[1] Florida Agricultural Experiment Station Journal Series No. N-00353.
[2] University of Florida, Institute of Food and Agriculture Sciences, Center for Aquatic Plants, Gainesville, FL.

Table 1
Herbicides Used In and Around Water for Management of Aquatic Vegetation

1976[1]	1990
Acrolein	Acrolein
Amitrole	Copper
Ammonium sulfate	2,4-D
Bromacil	Dichlobenil
Copper	Diquat
2,4-D	Endothall
Dalapon	Simazine
Dicamba	Fluridone
Dichlobenil	Glyphosate
Diquat	
Diuron	
Endothall	
Fenac	
Prometon	
Silvex	
Simazine	
Sodium chlorate	
Sodium metaborate	
Trichloroacetic acid	
2,4,5-T	

[1] Many of these products were registered under the FIFRA grandfather clause when the US Environmental Protection Agency was established. Several others were registered in some states. None are currently under patent protection.

Table 2
Characteristics of Pesticides Considered as Unacceptable

- Broad spectrum of activity to similar organisms.
- Toxicity and other adverse effects to nontarget organisms.
- Toxic metabolites.
- Fat soluble, which allows accumulation in organisms and biomagnification through the food chain.
- Fetal effects.
- Mutagenicity.
- Carcinogenicity
- Persistence and bioavailability in the environment.
- Interaction and synergism with other pesticides and additives.
- Disruption of the food chain.
- Opportunity for and impact of human exposure through use pattern.

Source: Carson 1962.

- Excessive amount of product stewardship required for the specialty aquatics market.

What characteristics of aquatic herbicides are considered unacceptable by environmentalists? Table 2 lists some of the characteristics of pesticides in general that raised the ire of ecologists such as Ms. Carson. Those familiar with the registration requirements of FIFRA realize that this list also represents many of the factors or criteria upon which current FIFRA guidelines for regis tration are based.

Table 3 lists the major characteristics or public concerns regarding pesticides as expressed in *Silent Spring* and indicates the degree of

Table 3
Environmental Characteristics of Current Aquatic Herbicides

Herbicide	Acute Toxicity: Rats LD_{50} mg/kg	Acute Toxicity: Bluegills LC_{50} mg/L	Broad Spectrum[1]	Biomagnification (in Food Chain), Carcinogenicity, and Mutagenicity	Persistence (Half-Life in Water, days)
Acrolein[2]	46	<1	+	-	-
Copper					
CuSO4	470	0.88	+	-	3
Chelated	650	1.2-7.5	+	-	3
2,4-D	300-1,000	168	-[4]	-	7.48
Dichlobenil	3,160	8.3	+	-	60-90
Diquat	230	245	+	-	1-7
Aquathol K	206	343	+	-	4-7
Hydrothol 191		0.94	+	-	4-7
Simazine	>5,000	16.0	+	-	30
Fluridone	>10,000	-	-[4]	-	20
Glyphosate	5,600	120	+[4]	-	14

[1] High degree (+); low degree (-).
[2] Western irrigation canals only.
[3] Varies depending upon formulation and water quality.
[4] Dependent on rate and timing of application.

applicability of the concern to the various aquatic herbicides. The current aquatic herbicides do not possess the characteristics generally deemed unacceptable. In particular, they are of low toxicity and are water soluble rather than fat soluble; thus, they do not accumulate within the food chain through biomagnification processes.

Operational Considerations

How are aquatic herbicide applicators perceived by most environmentalists? For the most part, herbicide users are seen by environmentalists and the public as managers with a limited knowledge of ecological relationships and a narrow management focus. There is also a feeling among the public that herbicide users have no regard for public health and welfare. The perception is that herbicides are used because it is cheaper than mowing and, as Rachel Carson (1962) claimed, "it gives them a giddy sense of power over nature." Another commonly held, unfounded belief of the public is that there is some financial incentive provided by the herbicide manufacturer or distributor to the public applicator to use more aquatic herbicide.

In spite of the above perceptions, the environmental community is not totally opposed to the use of herbicides. As stated by Ms. Carson, "Sometimes we have no choice but to disrupt the relationship of plants with other aspects of the environment. However, we must do so with full awareness that what we do may have consequences remote in time and place."

What characteristics of herbicide operational programs in public waters are generally unacceptable? Typically, those programs that routinely resort to nonselective blanket or broadcast spraying operations over large areas raise the ire of the environmental community and the public.

Surprisingly, there does appear to be acceptance of our maintenance control programs, wherein attempts are made to keep the nuisance plant at a low population through aggressive treatment at levels below problematic proportions. In fact, Ms. Carson endorsed recommendations of the 1957 Committee for Brush Control for Rights of Way (Egler 1953) as the manner in which herbicides should be used, i.e. "selective spraying wherein treatment is directed only to the weedy species in an attempt to select for more beneficial, native vegetation, thus preserving native wildlife habitat."

Ms. Carson identified the attributes of selective spraying that appealed to her as an ecologist. These were that it:

- Eliminates the need for broadcast, blanket spraying of herbicides.
- Causes less damage to nontarget plants and animals.
- Causes less human exposure.
- Manages vegetation as a community.
- Achieves long-term vegetation control and eliminates repeated massive blanket spraying.
- Minimizes the amount of herbicide used.
- Has lower annual costs.

Many examples of these types of operational programs and resulting benefits are available in the current aquatic plant management profession. Two notable examples are the recent management of waterhyacinths on Lake Okeechobee by the South Florida Water Management District and the on St. Johns River by the US Army Engineer District, Jacksonville.

Aquatic plant managers who are responsible for public waters are no longer driven only by the need to find a herbicide product that is labeled and efficacious. Today's managers are sensitive to public opinion, media coverage, and regulatory agency scrutiny. For these

reasons, public water resource managers tend to select control methods and herbicides that will reduce these pressures. Criteria on which a typical public aquatic plant manager bases decisions to use a given product include:

- Intended use of water and potential for conflict with human activities.
- Impact on nontarget plants and animals and other environmental impacts, such as persistence.
- Minimal or no water-use restrictions. No water reuse restrictions can eliminate the need for public notification or posting of water bodies.
- Costs per acre per season.
- Ease of use and length of control.

The standard by which Ms. Carson felt we should measure the environmental change brought about by our operations is the "need to preserve natural plant communities" (Carson 1962). Her hope was for the development of host-specific insects or pathogens that would suppress the nuisance species to only a small portion of the affected aquatic habitat and reduce the usage of pesticides. Is this not the long-term goal of our current research and management strategies for exotics such as hydrilla, waterhyacinths, Eurasian watermilfoil, and other exotic aquatic weeds?

The Future

From the above, it should be obvious that the future of the management of aquatic plants with herbicides will be determined by (1) the relative impact of the compounds on the environment and nontarget plants and animals, including man; (2) the perception by the public, media, and regulatory personnel of these compounds and how aquatic plant managers use them; (3) the financial resources available to support additional data requirements or aquatic registrations of new compounds; (4) government-industrial partnerships to maintain current registrations or to register new compounds; (5) combination of herbicides with other management techniques; (6) development of new and innovative application techniques to enhance selectivity and efficacy of current products; (7) education of the general public, media, and regulatory agency personnel; and (8) education of field applicators and managers on how to be more sensitive and responsive to public concerns.

The perception of the public and environmentalists is that *Silent Spring* still exists today. The message aquatic plant managers must send is that the pesticides pose no undue risk to man or the environment when properly utilized; otherwise, they would not be available on the market. Also, managers must emphasize that the overall goal of plant management is restoration and preservation of native habitats. Managers will also be required to know more about the chemical and biological characteristics of the compounds they use, to have well-stated goals, and to avoid overstating the safety or understating the impacts of the compounds they use or operations they perform.

In summary, will there be a future for aquatic herbicides in our management activities? Yes. Will the future be the same as today? Based on the past, probably not. Are aquatic plant managers changing to meet the new requirements? Yes, and probably more quickly and extensively than any other pest management profession because we are concerned about our most precious natural resource—water.

References

Anonymous. 1976. Herbicides used in and around water for management of aquatic vegetation. *Journal of Aquatic Plant Management* 14:80-81.

Carson, Rachel. 1962. *Silent Spring.* Houghton Mifflin, Boston.

Egler, F. E. 1953. Vegetation management for rights-of-way and roadsides. Pages 299-322 in Smithsonian Report for 1953. Smithsonian Institute, Washington, DC.

Herbicide Registration for Aquatic Use: A Look to the Future

by
John H. Rodgers, Jr.[1]

Since the formulation of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), the US Environmental Protection Agency (EPA) has had the responsibility for registration of herbicides for use in aquatic systems. In October 1988, FIFRA was revised and amended by Congress, and pesticide reregistration under new and more restrictive environmental rules was required to be accomplished 9 years from the date of these amendments. It is important to realize that herbicides constitute approximately 60 percent of all pesticides sales in the United States.

This important reregistration process and compliance with the new environmental regulations will not be without costs, however. The fee for reregistration is $150,000 per active ingredient. In addition, certain environmental data must be submitted, which are very costly to obtain.

Over the past decade, the EPA has been comparing the fate and effects of herbicides for use in aquatic systems. This has been a three-part exercise involving a strong research effort from their Ecological Risk (Ecorisk) Assessment Program.[2]

One aspect of the registration exercise has been to examine the fate and effects of pesticides from the viewpoint that contamination does not equal harm. As measurement techniques increased in sensitivity, it became apparent that residues of pesticides could often be found widely throughout aquatic systems. Also, it was apparent that certain low concentrations of these residues did not constitute harm or risk to nontarget species or human health.

A second important aspect of the registration process was an exercise in comparing the fate and effects of herbicides dispassionately with experimental evidence of their relative toxicology and persistence.

The third change that has evolved in the pesticide registration process over the last decade has been a recognition of the two sources of error that can lead to serious consequences in pesticide registration for aquatic use. The error that the EPA must avoid is concluding that a pesticide is not toxic when it proves to be toxic in a particular situation, or that a pesticide does not pose a particular risk and it proves to be harmful in a specific authorized use.

The converse source of error, to say that a pesticide is toxic when it is not in a particular use scenario, is perhaps equally damaging. In this scenario, society has been denied the use of a potentially valuable chemical such as an aquatic herbicide that may solve a problem. Attempts have been made to minimize these sources of error by strategic research efforts, as well as education of users to understand the risks associated with approved uses of herbicides.

This paper focuses on two areas: the pesticide registration process as it is currently conducted, and a look to the future of registration of herbicides for aquatic uses.

[1] University of Mississippi, Department of Biology, Biological Field Station, University, MS.
[2] Information in this paper is presented with the acknowledgment of Mr. Jim Ackerman, Ecological Effects Branch, Office of Pesticide Programs, US Environmental Protection Agency, Washington, DC.

Currently, herbicides designated for aquatic use undergo a review of both toxicological and exposure data. First, the toxicological data are requested and evaluated using a tiered approach. The initial tier of data generally focuses on the acute toxicity of the herbicides to target and nontarget species. Aquatic herbicides may be intended for nonvascular or vascular plants. Nontarget species of concern would include both invertebrates and fish Invertebrates such as microcrustaceans and insects would be of concern, and toxicological data from these invertebrates may be required. Toxicological studies of fish of concern, such as the bluegill sunfish (*Lepomis macrochirus*), may be required.

If concerns arise in the initial tier, additional and more detailed data may be required to examine the chronic effects of the herbicide on nontarget species. Chronic effects are especially of concern if the pesticides persist for more than 4 to 20 days. Again, species of concern may include crustaceans, insects, and other invertebrates, as well as vertebrates such as salamanders and fish. The duration of the chronic tests may range from about 3 weeks to 2 years. These tests are relatively costly and require considerable attention and expertise to conduct.

If a herbicide intended for aquatic use persists, and the results of the intermediate tier of testing indicate cause for concern, a third or final tier of testing may be required, which includes mesocosm or field studies. These field studies may be quite expensive (in excess of $1 million per study).

To make the decisions at each tier, the concentrations of a herbicide which cause effects are compared to expected environmental concentrations (EECs) that may be predicted or measured in field trials. The EECs obtained in field trials may be acquired during preliminary use of the herbicide under an experimental use permit.

Estimation of the exposure or EEC is crucial to making an accurate decision whether to proceed with registration or to deny registration of a particular herbicide. The technique currently used by the EPA to arrive at this decision is called the quotient method. In the quotient method, the concentrations of herbicide causing effects are compared to the EEC or exposure concentration that the nontarget species may encounter.

For a variety of categories of pesticide registration, certain herbicide label requirements may be imposed (as well as restricted use), requiring that users be trained under a certification program. At each step along this decision path, the weight of the scientific evidence is evaluated, and presumptions of unacceptable risk must be negated. This requires both risk assessment and risk management decisions. The risk management decisions would involve a benefit analysis that would incorporate concerns for the benefits to society versus the risk to the environment or nontarget species.

It is important to remember that the Federal registrations under the EPA are the most liberal registrations in the sense that each State may be more restrictive. In other words, each State may consent to FIFRA registrations or impose additional restrictions on the utilization of herbicides within its boundaries. For reservoirs, lakes, or rivers with waters falling within the bounds of two adjacent States, the restriction or the herbicide use is usually regulated by the more restrictive State.

The pesticide registration process under FIFRA is currently undergoing review and potential revision. There is concern that new scientific techniques and risk assessment approaches have been developed and that these approaches should be incorporated into the pesticide registration process.

The EPA, pesticide manufacturers, and environmental professionals have initiated this review and discussion under the auspices of the Conservation Foundation and the World Wildlife Fund. An Aquatic Effects Dialogue Group has been working for more than a year to evaluate the current pesticide registration

process and to suggest changes in the process that might be more defensible or may lead to more lasting scientifically defensible registrations.

It is apparent that the new regulations will require more toxicological testing rather than less testing. Additional plant species will be required in addition to the nonvascular and vascular plants currently tested. Also, other fish species may be required. More pesticides will probably be tested in the higher tiers, including microcosms and mesocosms. These are particularly useful systems for evaluating effects on nontarget species.

A third requirement in specific situations may be the field monitoring of residues for a period of years to ensure that estimated environmental exposures are not being exceeded. It has been suggested that the EPA develop probabilistic approaches to estimating environmental exposure concentrations as well as toxicological hazards associated with pesticide use. Any of the new regulations will probably lead to label changes. These label changes may require buffer zones, intervals between treatments, or considerations for lower exposure concentrations.

The new regulations are likely to give additional attention to human health and worker exposure, as the formulations of pesticides are submitted for registration.

Probably the most important aspect of new regulations or approaches to registering pesticides for aquatic use would be a decrease in the "worst-case" philosophy. Frequently, estimated exposure concentrations for pesticides are based on worst-case assumptions, as well as the toxicological data to which these exposures are compared. With both of these as worst-case assumptions, we currently have a very conservative situation as far as the margin of safety for the use of pesticide.

As nuisance aquatic plant problems become more intense and widespread, and as the chemicals registered for aquatic use become fewer and fewer, there is doubt that we can support the luxury of the unnecessarily large margins of safety between exposure concentrations and effects on nontarget species.

In addition to the new regulations and approaches for aquatic registrations of herbicides, one would expect that the pesticide industry would respond with new materials. These new materials would probably focus on three areas. The first area would be new uses or formulations of existing materials. This would include development of control-release systems as well as delivery systems that minimize off-target movement of the pesticides.

A second development that will probably transpire is new and modern chemistries. There will probably be an intense focus on more natural products or naturally occurring herbicides and plant growth regulators. An intense effort is currently centered around "designer herbicides" that are developed using molecular structure-activity relationships that have been programmed into a computer. This requires a highly developed understanding of chemical activity, as well as a thorough understanding of plant physiology, mode of action, and movement of these materials to active sites. These modern chemicals should give rise to more target specificity; this means that the modern pesticide should be more like rifles than shotguns in their action. They will minimize impacts on nontarget species while maximizing the control of the target species.

In addition, we can anticipate that microbial herbicides will receive considerable attention. These may be developed based on the *Bacillus thurengensis* model. These herbicides may consist of bacteria or fungi that are pathogens which are host-specific for aquatic plants. This host specificity may be conferred by genetic engineering or through other approaches.

This is an interesting and crucial time for registration of aquatic herbicides under FIFRA. The list of currently available herbi-

cides for aquatic use is not large.[1,2] Under the reregistration process, some of the currently registered chemicals may not be considered by manufacturers for reregistration. Registrations may be denied based on the new toxicological and safety margin requirements.

Additions of herbicides to currently registered aquatic products may include such compounds as triclopyr and bensulfuron methyl. However, not many additional materials are "in the pipeline" for registration, for a variety of reasons.

Herbicides have been widely used throughout the history of aquatic plant management. Most of these uses have resulted in minimal impacts on nontarget species. The EPA might argue that this is a success story for their registration process. Clearly, with their concerns for protection of nontarget species, it is unlikely that the registration process will become simpler or less costly.

As the interest in the Nation's waterways grows and as the population increases (placing more pressure upon these waterways), there is a high probability that the interest and need for aquatic herbicides will grow concomitantly. As these needs become apparent and as the cost of aquatic plant management using herbicides increases, new chemicals will probably be developed to meet the demand.

Despite the cost to ensure environmental safety, it is likely that pesticide manufacturers will respond to the need for modern materials that can meet the environmental standards that we establish.

---

1 K. H. Reinert and J. H. Rodgers, Jr. 1987. Fate and persistence of aquatic herbicides. *Reviews of Environmental Contamination and Toxicology* 98:61-98.

2 H. E. Westerdahl and K. D. Getsinger, eds. 1988. Aquatic plant identification and herbicide use guide, 2 vols. Technical Report A-88-9. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Simulation Control Technology

Historical Perspective and Overview

by
R. Michael Stewart[1]

Historical Perspective

The US Army Engineer Waterways Experiment Station (WES) initiated development of computer-based simulation models in support of the Aquatic Plant Control Research Program (APCRP) during the 1970s. Several simulation models were developed during these early efforts, including the HARVEST mechanical control simulation model and the White Amur Stocking Rate model. These models are discussed in the following sections.

HARVEST model

The WES HARVEST mechanical control simulation model includes algorithms that simulate aquatic plant control cutting operations, collecting operations, over-water transporting operations, and upland disposal (trucking) operations. As an analytical tool, the HARVEST model allows the user to test overall operational productivity (i.e., acres harvested per hour or tons of plant material harvested per hour) of existing or new designs of mechanical harvesting systems under "user"-defined operational and environmental conditions.

During execution of the HARVEST model, the user is allowed to define, through a series of model inputs (Table 1): (1) performance specifications of the mechanical system to be evaluated and (2) operational and (3) environmental conditions of the site to which mechanical control is to be applied.

HARVEST model output (Table 2) provides a summary of the results of the simulation and is then used to evaluate overall system productivity of the simulated mechanical harvesting operation. Examination of model output also allows the user to determine which mechanical harvesting operation(s) (i.e., cutting, collection, transporting, or onshore disposal) limits overall system productivity. This information can then be used to plan for a more effective mechanical harvesting operation. Examples of specific applications of the HARVEST model can be found in Hutto (1982, 1984), Sabol (1983), and Sabol and Hutto (1984).

Table 1
Input Requirements of the HARVEST Model

Equipment Performance Parameters
Harvester Cutter Width, ft
Harvester's Maximum Forward Speed, ft/min
Harvester's Maximum Volumetric Throughput, cu ft/hr
Harvester's Turning Time, min
Harvester's Effective Storage Capacity, cu ft
Transporter's Changing Time, min
Transporter's Speed (loaded), ft/min
Transporter's Speed (empty), ft/min
Transporter's Docking and Setup Time, min
Transporter's Unloading Rate, tons/min
Truck Speed (loaded), mph
Truck Speed (empty), mph
Truck Unloading Time, min
Truck Capacity, cu yd
Rental Rate for Each Piece of Equipment, $/hr
Operational Parameters
Harvesting Site Dimensions, ft
Distance from Harvesting Site (nearest corner) to Shore Takeout Point, ft
Distance from Shore Takeout Point to Upland Disposal Site, miles
Environmental Parameters
Mean Harvestable Density of Aquatic Plants, tons/acre
Mean Stacked Density of Harvested Plant Material, lb/cu ft

---

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Table 2 **Summary of HARVEST Model Output**
Total Size of Harvested Site, acres
Total Mass of Plant Material Harvested, tons
Total Number of Harvester Loads
Total Time of Harvesting Operation, hr
Average Speed of Harvester, ft/min
Swath Width of Harvester, ft
Percent Utilization of Harvester for Actual Harvesting
Areal Productivity of Harvesting Operation, acres/hr
Mass Productivity of Harvesting Operation, tons/hr
Total Harvesting Operation Cost and Cost per Acre, $
Trucking cost, $

STOCK model

The WES White Amur Stocking Rate model (AMUR/STOCK Version 1.0) is a biological control simulation model that provides information useful for determining proper stocking rates of diploid white amur for control of dioecious hydrilla. This model was developed during the "Large-Scale Operations Management Test (LSOMT) of Use of the White Amur for Control of Problem Aquatic Plants in Lake Conway, Florida." A description of the algorithms and example applications of the AMUR/STOCK model are provided in Miller and Decell (1984). User inputs to the model that describe the environmental conditions of the water body infested with the target plant (e.g. hydrilla) and information on the proposed operational stocking plan are shown in Table 3.

Table 3 **Input Requirements of the AMUR/STOCK Model**
Area of Photic Zone of Lake, acres
Current Area of Lake Infested with Hydrilla, acres
Maximum Seasonal Density of Hydrilla, tons/acre
Month to Stock White Amur
Duration of Simulation, months
Number of White Amur to Stock
Average Weight of Fish to Stock, lb

Output from the AMUR/STOCK model gives monthly estimates of the remaining plant infestation and the white amur population levels for the period of the simulation. This output provides the user with information on the effectiveness of a proposed operational stocking of white amur during the specified time period.

Initially, both the HARVEST model and the AMUR/STOCK model were implemented on a mainframe computer at WES. Consequently, user access to these models was somewhat limited. In the early 1980s, both models were revised for execution on personal computers (PCs) and were made available for release during 1983. By 1989, WES had transferred over 150 of these models to various government agencies, organizations, and private businesses.

Development of Computer-Aided Simulation Procedures

In fiscal year (FY) 1985, the APCRP established a new thrust area entitled Computer-Aided Simulation Procedures. This thrust area was established to provide focus for this important technology area and to consolidate future APCRP model development efforts. Sabol (1985) identified the long-range goals of the newly created technology area and included a list of target aquatic plants and operational control techniques for which simulation models could be developed. Current work includes development of simulation models for the plants and control techniques listed in Table 4.

To support the goals of the Computer-Aided Evaluation Procedure technology area, four research task areas have been established: (1) plant growth simulations, (2) biological control simulations, (3) chemical control simulations, and (4) aquatic plant database development. Brief descriptions of these task areas are presented in the following sections.

Plant growth simulations

Objective. The objective of this task area is to develop PC-based plant growth models for waterhyacinth, hydrilla, Eurasian watermilfoil, and waterlettuce. These plant growth models will be structured to function independently or as functional modules within "coupled" simulation models of biological and chemical control techniques.

Table 4
Target Aquatic Plants and Operational Control Techniques for Which Simulation Models Are Being Developed

Target Plant	Category of Control	Control Technique/Agent
Waterhyacinth	Chemical	2,4-D (DMA) Diquat
	Biological	*Neochetina eichhorniae* *Neochetina bruchi*
Hydrilla	Chemical	2,4-D (BEE) Diquat Endothall Fluridone
	Biological	White amur *Bagous affinis* *Hydrellia pakistanae*
Eurasian watermilfoil	Chemical	2,4-D (BEE) Diquat Endothall Fluridone
	Biological	White amur

The developmental effort includes (1) development of a generalized conceptual framework for plant growth models of aquatic plant species, (2) for each plant species, development of a first-generation computer-based plant growth model that will simulate the biomass growth of an infestation of the targeted plant over a range of time periods under user-selected environmental conditions, (3) testing of the functional relationships used in the model with laboratory and controlled field data, (4) coordination with APCRP plant ecology researchers to develop improved plant growth relationships for incorporation into the plant growth models, as these needs are identified in testing (element 3 above), and (5) release of PC-based versions of the models to interested users.

Accomplishments through FY 90. Generalized conceptual models for plant growth have been developed for both floating and submersed aquatic plants. First-generation plant growth models were completed for waterhyacinth in FY 87 (Akbay, Wooten, and Howell 1988), for hydrilla in FY 89 (Wooten 1989, 1990), and for Eurasian watermilfoil in FY 90. Validation tests for the waterhyacinth and hydrilla plant growth models have been conducted with available laboratory data and with field data from Florida and Texas. Controlled field studies have been designed and were initiated at the Lewisville Aquatic Ecosystem Research Facility (LAERF) to develop improved plant growth relationships for the waterhyacinth model. A 3-year field data collection effort was initiated in FY 90 at Guntersville Reservoir to provide validation data for testing and refinement of hydrilla and Eurasian watermilfoil plant growth models.

FY 91 activities. Activities scheduled for FY 91 will focus on continued collection of validation data sets for further testing of existing first-generation plant growth models. Field validation data will be collected at monthly intervals for hydrilla and Eurasian watermilfoil growth at Guntersville Reservoir, Alabama. Researchers at the LAERF will continue collecting controlled field validation data for testing of the waterhyacinth growth model. As part of these studies, data are being collected to test and refine relationships for waterhyacinth respiration during winter periods. Additionally, data will be collected to test relationships for other plant growth processes as influenced by seasonal changes in environmental conditions, and also as affected by gross differences in water nutrient levels.

Biological control simulations

Objective. In this task area, PC-based simulation models of the various biological control agents available for aquatic plant control are being developed. These models are being structured as three major modules or components. Module I will address responses of biocontrol agent populations to specified conditions of temperature and solar radiation over a selected time period. Module II will generate a plant growth simulation for the targeted plant infestation under the same environmental conditions and time period. This module will be a functional version of the appropriate plant growth model discussed above. Module III will account for ecological interactions between the biocontrol

agent population and the plant population. The primary function of Module III is to predict the damage that the biocontrol agent population will inflict on the targeted plant infestation.

Work to be conducted includes (1) development of a generalized conceptual framework for a simulation model of biocontrol agents, including a biocontrol agent population dynamic module and a biocontrol agent host-plant interaction module, (2) development of a first-generation computer-based biological control model that simulates the effects of specific biocontrol agents on their host plant, (3) testing of the functional relationships of the separate modules, and of the coupled modules, with available laboratory and field data, (4) coordination with APCRP biocontrol technology researchers to develop improved relationships for modeling biocontrol systems, and (5) release of documented PC-based versions of the models to interested users.

Accomplishments through FY 90. Generalized conceptual models have been developed for fish and insect biocontrol agents of aquatic plants. A first-generation model (INSECT) of the waterhyacinth and *Neochetina* weevil biocontrol system was completed in FY 87. Akbay, Wooten, and Howell (1988) give a detailed description of the INSECT model. Continued validation efforts of the INSECT model have identified several processes of the *Neochetina* and waterhyacinth biocontrol system which require additional research (Akbay, Wooten, and Howell 1988; Grodowitz and Stewart 1989; Howell and Stewart 1989). In this regard, collaborative research has been undertaken at the LAERF. Additionally, a revised White Amur Stocking Rate model was developed in FY 89. The revised model allows simulations to be produced for impacts of this biocontrol agent on multiple plant species. Example applications of this model are provided by Boyd and Stewart (1990) and by Boyd and Stewart (1991) for conditions at Guntersville Reservoir.

FY 91 activities. An interim User's Manual for the INSECT model will be completed and distributed to selected agencies for evaluation during FY 91. Additionally, development of a second version of this model will be initiated for the *Hydrellia pakistanae* and hydrilla biocontrol system. Data collection efforts and validation testing of the White Amur Stocking Rate model will also be accomplished.

Chemical control simulations

Objective. The objective is to develop PC-based simulation models for available chemical control techniques. These models will also consist of separate modules. Module I will generate simulations for the fate of herbicides in the environment following application. This information will be used to calculate an exposure of the target plant infestation to the herbicide. Module II will determine percent mortality to the target plant infestation resulting from the exposure. Module III will be a functional version of the appropriate plant growth model and will produce a simulation for the "regrowth" of the treated plant infestation following the simulated herbicide application.

The development effort for the chemical control simulation model is similar to that described above for plant growth and biological control simulations. All research activities undertaken to develop improved relationships for processes affecting chemical control techniques are being coordinated closely with researchers in the Chemical Control Technology area.

Accomplishments through FY 90. A generalized conceptual framework for a coupled herbicide fate and target plant response model was completed during FY 87. A first-generation model, HERBICIDE, was completed during FY 88 (Clifford, Rodgers, and Stewart 1989). This initial version of the HERBICIDE model includes relationships for the fate of aerial-applied 2,4-D (DMA) and the resulting effects of the application on

waterhyacinth. Validation testing of this model was continued through FY 89 (Clifford, Rodgers, and Stewart 1990). A new version of the HERBICIDE model was also developed during FY 90 which includes fate and effects relationships for applications of four other herbicides (2,4-D (BEE), diquat, endothall, and fluridone) on hydrilla and Eurasian watermilfoil (Rodgers, Clifford, and Stewart 1991).

FY 91 activities. During FY 91 a User's Manual and Technical Report will be prepared on the HERBICIDE (Version 1) model, and the model will be distributed to interested users. Additionally, validation tests will be conducted for fate and effects relationships included in the new version of the model.

Aquatic plant database development

Objective. The objective of this research area is to develop comprehensive environmental databases, in digital format, that are compatible with computer-based simulation models of plant growth and biological and chemical control techniques. These databases will contain information for specified water bodies on plant infestation levels, weather conditions, and other site-specific environmental conditions that affect aquatic plant growth and control technique effectiveness. Work efforts will include compiling database information on selected water bodies, developing digital databases for this information, and demonstrating the applicability of these databases for development, evaluation, and use of aquatic plant control simulation models.

Accomplishments through FY 90. A two-level database structure was designed to provide information on a broad geographical base (Level I) and on a site-specific base (Level II). The Level I database will contain regional weather data and will be used in conjunction with the simulation models to evaluate the effects of different geographical weather conditions on aquatic plant growth and control technique impacts. The Level II databases will contain site-specific information for environmental conditions in selected water bodies. Level I databases have been developed for Florida, Lousiana, Texas, and Tennessee in the southeastern region. Level II databases are under development for Lake Marion, South Carolina (Welch and Remillard 1991), and for Guntersville Reservoir, Alabama (Kress, Causey, and Ballard 1990).

FY 91 activities. During FY 91, Level I databases will be developed for the Midwestern and North Pacific regions. Level II database development will continue at Lake Marion and at Guntersville Reservoir. Additionally, the coupling of Level II databases and aquatic plant control simulation models will be demonstrated for the Guntersville Reservoir database.

References

Akbay, K. S., Wooten, J. W., and Howell, F. G. 1988. Simulation model of waterhyacinth and its biocontrol agents; Report 1, First-generation model. Technical Report A-88-8. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Boyd, W. A., and Stewart, R. M. 1990. Preliminary simulation results of triploid white amur stocking rates for Guntersville Reservoir using AMUR/STOCK (Version 1.5). Pages 247-260 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Boyd, W. A., and Stewart, R. M. 1991. See pp 266-278 in this proceedings.

Clifford, P. A., Rodgers, J. H., Jr., and Stewart, R. M. 1989. Further development of herbicide fate and target plant species effects model. Pages 274-282 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Clifford, P. A., Rodgers, J. H., Jr., and Stewart, R. M. 1990. Comparisons of HERBICIDE model simulation results with field measurements. Pages 261-270 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Grodowitz, M. J., and Stewart, R. M. 1989. Validation studies in Texas for the model INSECT. Pages 257-273 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Howell, F. G., and Stewart, R. M. 1989. Applications of INSECT, A computer model of waterhyacinth and *Neochetina* population dynamics. Pages 251-256 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hutto, T. D. 1982. Simulation modeling of mechanical control systems. Pages 33-50 in *Proceedings, 16th Annual Meeting, Aquatic Plant Control Research Planning and Operations Review.* Miscellaneous Paper A-82-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hutto, T. D. 1984. Demonstration of utility of HARVEST model. Pages 36-42 in *Proceedings, 18th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-84-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kress, M. R., Causey, E. M., and Ballard, J. R., Jr. 1990. Digital database to support aquatic plant control modeling. Pages 271-282 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, A. C., and Decell, J. L. 1984. Use of the white amur for aquatic plant management. Instruction Report A-84-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Rodgers, J. H., Jr., Clifford, P. A., and Stewart, R. M. 1991. See pp 279-282 in this proceedings.

Sabol, B. M. 1983. Simulated mechanical control of aquatic plants in Buffalo Lake, Wisconsin. Miscellaneous Paper A-83-8. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sabol, B. M. 1985. Development of computer-aided evaluation systems. Pages 61-65 in *Proceedings, 19th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-85-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sabol, B. M., and Hutto, T. D. 1984. Simulating mechanical control operations. Aquatic Plant Control Research Program Information Exchange Bulletin, Vol A-84-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Welch, R., and Remillard, M. 1991. See pp 283-289 in this proceedings.

Wooten, J. W. 1989. Description and update: An improved hydrilla growth model. Pages 283-289 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wooten, J. W. 1990. Plant growth simulation models for hydrilla and Eurasian watermilfoil. Pages 240-246 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research* Program. Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Plant Growth Simulation Models

by
Jean W. Wooten[1] *and R. Michael Stewart*[2]

Introduction

The Aquatic Plant Control Research Program has sponsored the development of computer-based plant growth simulation models to assist in the transfer of information on nuisance levels of aquatic plant growth to aquatic plant managers. In this regard, the models have been designed to provide users with information relevant to temporal occurrences and levels of aquatic plant infestations under water body-specific environmental conditions. Additionally, these models are designed to interface with simulation models of biological and chemical control techniques and to generate information useful for implementing effective aquatic plant management activities.

First-generation plant growth models have been completed for waterhyacinth (*Eichhornia crassipes* (Mart.) Solms), hydrilla (*Hydrilla verticillata* (L.f.) Caspary), and Eurasian watermilfoil (*Myriophyllum spicatum* L.). Earlier descriptions of these models are provided in Akbay, Wooten, and Sabol (1988) and Wooten (1989, 1990). This paper provides a brief overview of the hydrilla (HYDRILLA) and Eurasian watermilfoil (MILFOIL) models. Additionally, the simulation results for Eurasian watermilfoil plant biomass generated by the MILFOIL model are compared with the plant biomass estimates from 1990 field studies conducted at Guntersville Reservoir, Alabama.

Overview of the Models

Model characteristics

Because the plant growth models are being developed to function as technology transfer tools, the models have been designed with the following characteristics in common:

- The models shall function on all PC/DOS-compatible personal computers, with the restriction that an 80287 math-coprocessor be installed in the machine.
- The models shall execute in a user-friendly, interactive mode, which requires minimal user entry of information.
- Weather data needed to support model execution shall be provided as part of the software package.
- Simulation calculations shall be made on a daily basis during the simulation period, and results for each update period shall be available through tabular screen display, graphical screen display, or hard-copy output.
- The simulations shall be generated for any number of days, up to a maximum period of 3 years (i.e. 1,095 days).

[1] University of Southern Mississippi, Department of Biological Sciences, Hattiesburg, MS.
[2] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Model input requirements

Though user input requirements to the models have been minimized in an effort to maintain user-friendliness, the models do request the following information from the user during execution:

- The Julian day (i.e., calendar day 1 through 365) for the first day of the simulation period.
- The number of years of the simulation period.
- The Julian day for the last day of the simulation period.
- The choice of available weather data files to use in the simulation.
- The dry weight plant biomass (kg/m^2) on the first day of the simulation period.
- A choice as to whether the plants in the simulation will overwinter "intact" or experience "dieback."
- The average depth of the water body.
- The Secchi depth disk of the water body.
- For the hydrilla model only, an estimate of the level of tuber production (i.e., High, Medium, or Low) to be used for the simulation, and a choice as to whether mature tubers are present on the first day of the simulation. (If Yes, the number of tubers per square meter on the first day is also required.) Additionally, during initialization of the HYDRILLA model, the user must select a pH range from a list of choices that best describes conditions in the water body.

Assumptions of the models

In the development of all first-generation simulation models, basic assumptions regarding important process relationships must be made in order to overcome lack of complete knowledge of the system being modeled. During development of the first-generation hydrilla and Eurasian watermilfoil plant growth models, the following basic assumptions regarding important plant growth processes were made:

- The photosynthetic and respiration rates of the plants are functions of the prevailing temperature and light intensity; past temperature and light experience have no effect on the current rates other than by affecting the mass of the plants for the previous simulation update period.
- No adaptive changes in leaf structure or function are made by the plants in response to environmental conditions.
- Day and night plant respiration rates are equal.
- The rates of plant respiration are not dependent on plant size and age.
- Plant growth is not limited by nutrient levels in the water body.

Preliminary Comparisons of MILFOIL Model Simulation Results with Guntersville Reservoir Field Data

Plant biomass estimates for Guntersville Reservoir

As part of the 5-year Guntersville Reservoir aquatic plant management project being jointly conducted by the Tennessee Valley Authority (TVA), the US Army Engineer Waterways Experiment Station (WES), and the US Army

Engineer District, Nashville, Eurasian watermilfoil (hereafter referred to as milfoil) biomass samples were collected in Guntersville Reservoir during 1990. Site locations were selected from aerial photographs taken in late summer 1989, in an effort to locate sites within established milfoil colonies. Sites were sampled at monthly intervals from April through October, and again in December 1990. Samples were collected using the WES square-head submersed aquatic plant biomass sampler described by Sabol (1984). This sampling device is designed to collect all plant material within a 0.39-m^2 area of the water column.

Summaries of the plant biomass data are given for the three milfoil sites in Table 1. These data indicate that plant growth at the Chisenhall and Brown's Creek sites produced significant increases in milfoil biomass during the growing season. Plant biomass estimates at these two sites increased through the summer months and then declined to levels similar to those recorded in April 1990 samples during the fall and winter months. Plant biomass estimates at the Pine Island site, however, did not show these typical patterns of milfoil growth.

Table 1
Summary of Water Depths and Monthly Plant Biomass Estimates at the Three Milfoil Sites

Site Identification	Water Depth (Mean ± SD)		Date of Collection	Plant Biomass[1] (Mean ± SD)	
Chisenhall	2.16	0.19	4/24/90	0.0362	0.0392
			5/22/90	0.0870	0.0935
			6/25/90	0.1619	0.1379
			7/24/90	0.5258	0.3976
			8/21/90	1.0280	0.8106
			9/18/90	0.5938	0.4267
			10/15/90	0.3924	0.2978
			12/11/90	0.0685	0.0541
Brown's Creek	2.28	0.40	4/26/90	0.0159	0.0177
			5/23/90	0.1117	0.1032
			6/27/90	0.2155	0.2795
			7/25/90	0.7036	0.6340
			8/22/90	0.6914	0.8371
			9/20/90	0.6991	0.8097
			10/17/90	0.3317	0.4397
			12/12/90	0.0785	0.1232
Pine Island[2]	2.58	0.15	4/25/90	0.0190	0.0189
			5/22/90	0.0185	0.0207
			6/26/90	0.0081	0.0111
			7/24/90	0.0016	0.0038
			8/21/90	0.0002	0.0007

[1] Mean values reported as kilograms per square meter (fresh weight).
[2] Sample collection was discounted at the Pine Island site after August due to the limited amount of milfoil growth.

MILFOIL model simulation results

The MILFOIL plant growth simulation model was used to generate daily estimates of plant biomass for comparison with estimates from the monthly field data for the Chisenhall site. The MILFOIL model was initialized to begin a simulation on Julian day 112 (24 April) and end on Julian day 365. Meteorological conditions for initializing the model for Guntersville Reservoir were compiled from historical records and updated with actual field measurements where possible.

Number of daylight hours was calculated for Guntersville Reservoir (latitude 34.3 deg N) by interpolation of values reported for other latitudes (Figure 1). Solar radiation values are average daily solar radiation values reported for Nashville, TN, for the 4-year period 1977 through 1980 (Figure 2).

Water temperatures are derived from temperatures reported by TVA for Guntersville Reservoir at Nickajack Dam tailrace for the 5-year period 1980 through 1984 (Figure 3). The Secchi disk depths were calculated by interpolating between Secchi readings measured at the Chisenhall site on the nine 1990 sampling dates (Figure 4). Water depth was set at 2.2 meters (Table 1).

Dry weight plant biomass for model initialization was 0.004 kg/m^2, a value approximating 10 percent of the 24 April 1990 fresh weight biomass estimate for the Chisenhall site (Table 1).

A comparison of plant biomass estimates generated by the MILFOIL model with estimates from the Chisenhall field study is provided in Figure 5. In this figure, field data are plotted as means, with vertical bars representing the 95-percent confidence intervals ($T_{0.025,24}$) of the

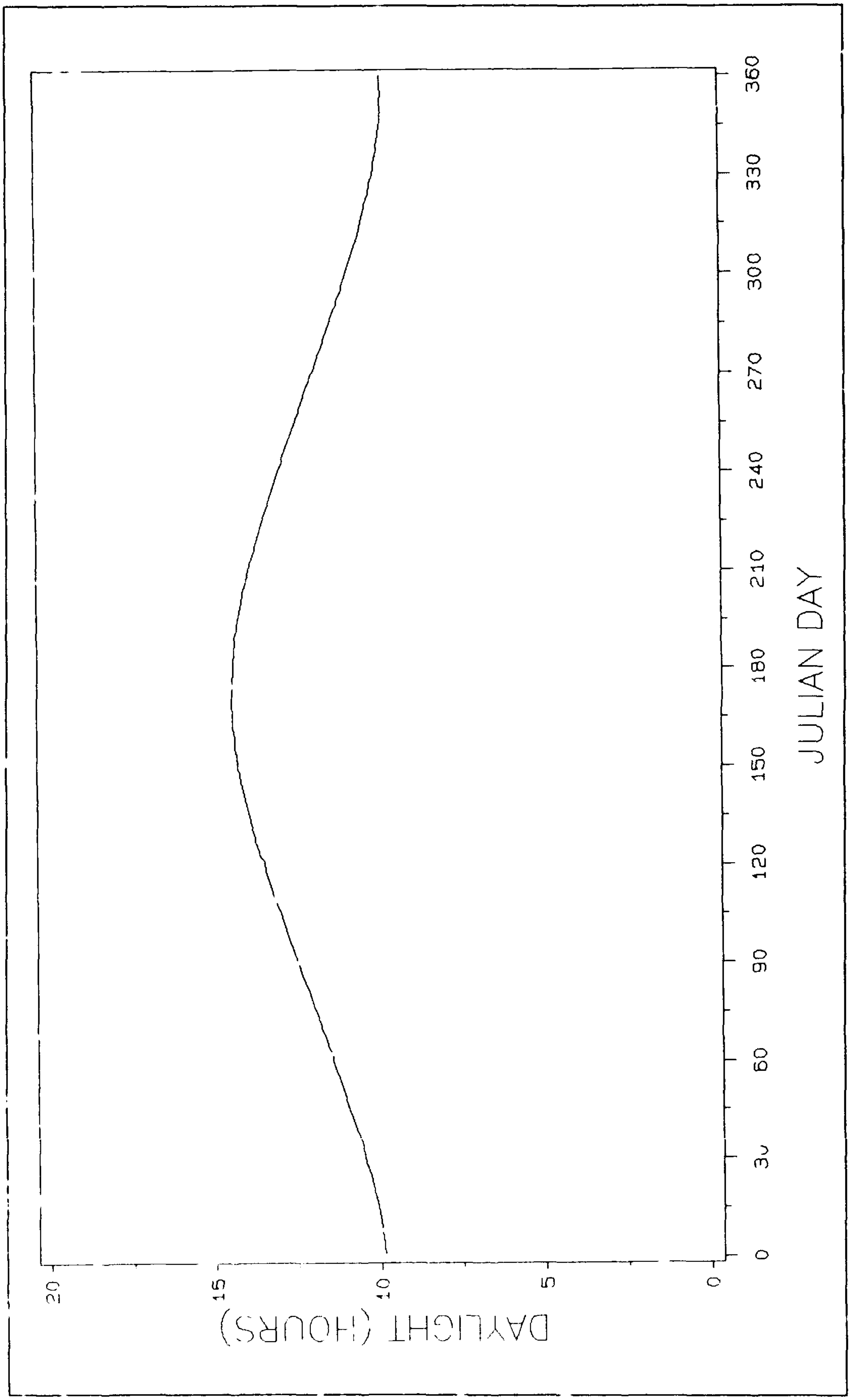


Figure 1. Length of daylight period for Guntersville Reservoir. (Calculated by interpolation for latitude 34.3 deg N)

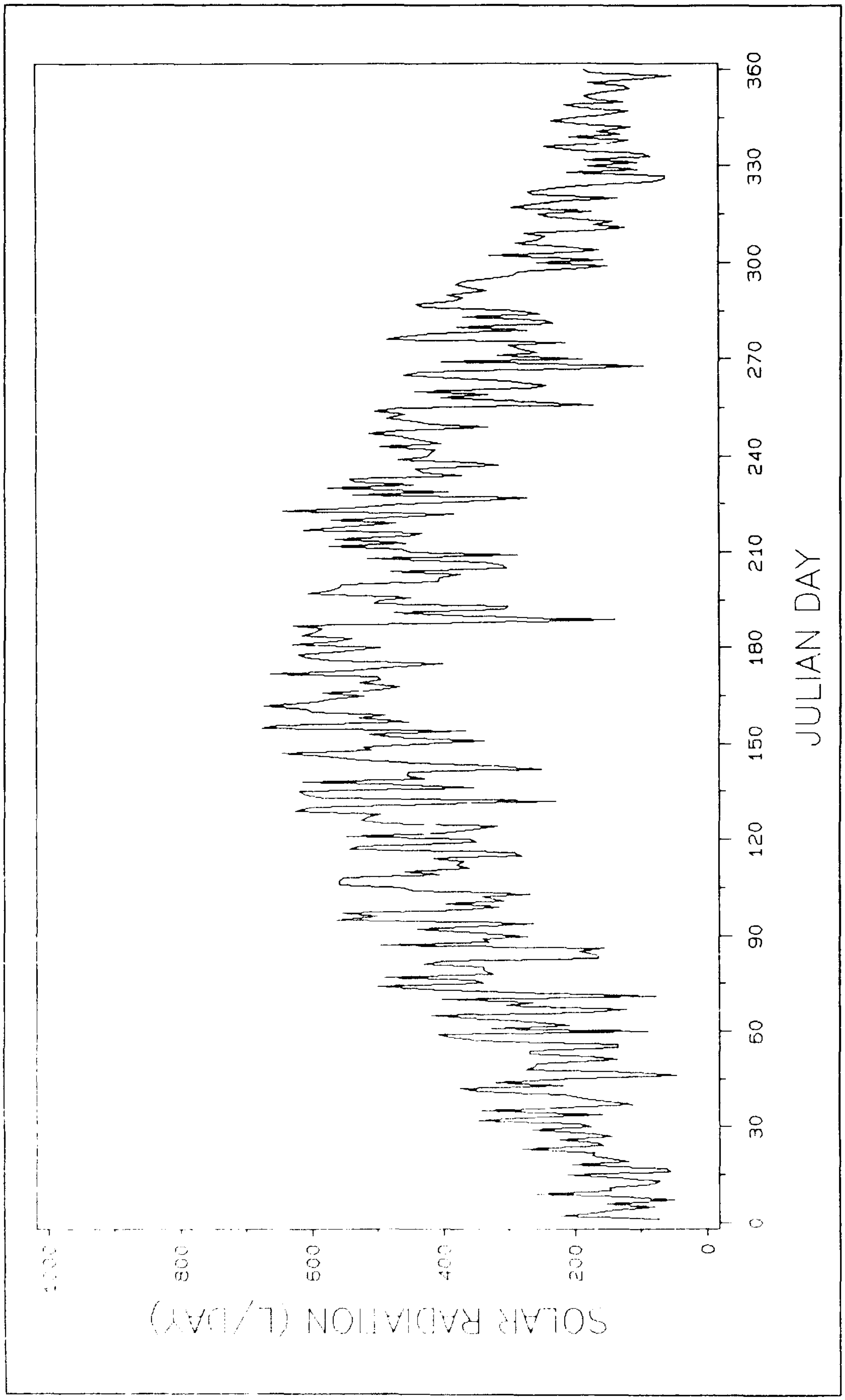


Figure 2. Average daily solar radiation (Langleys/day) reported for Nashville, 1977-1980

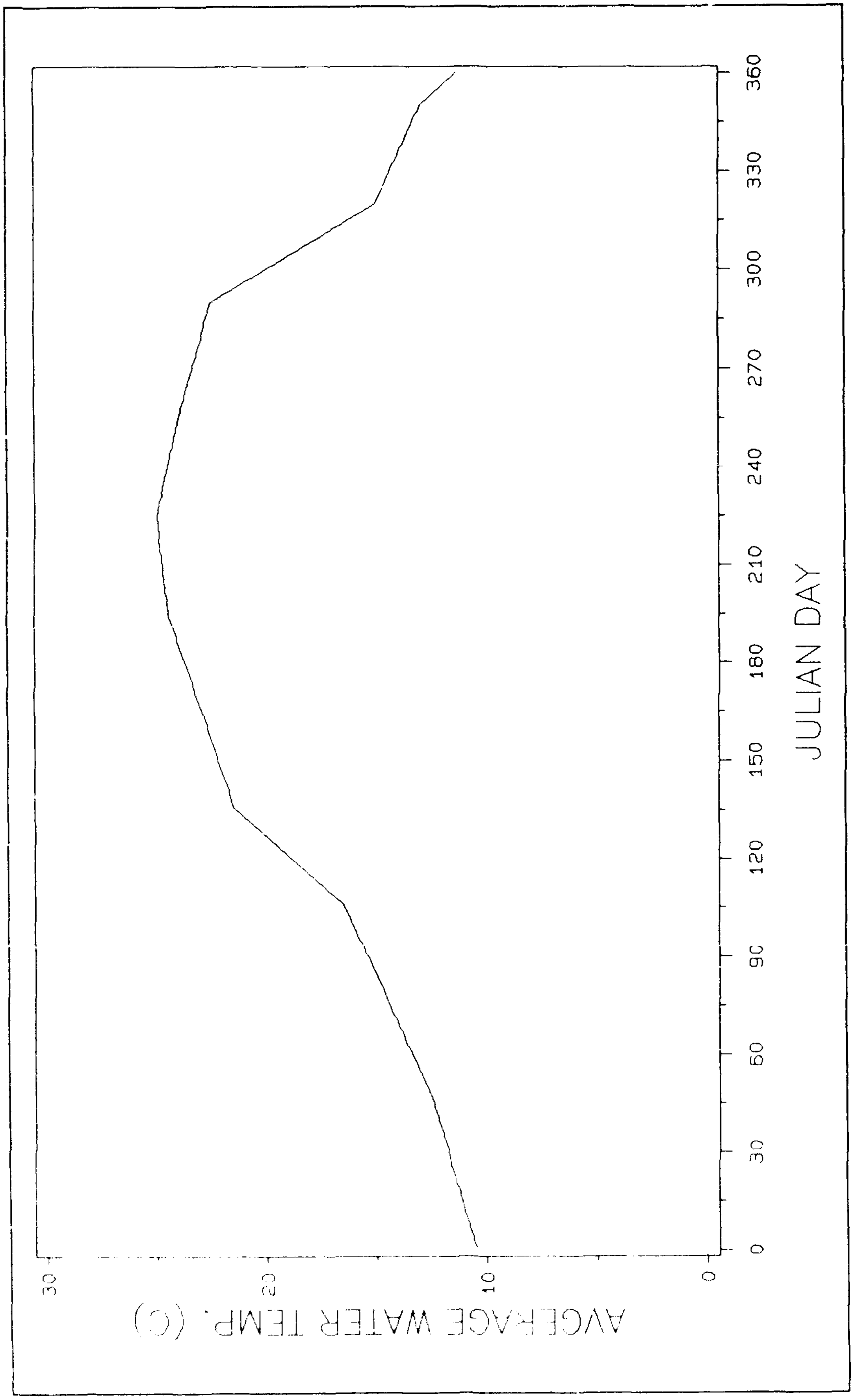


Figure 3. Average water temperatures (°C) for Nickajack Dam tailrace, Guntersville Reservoir, 1980-1984

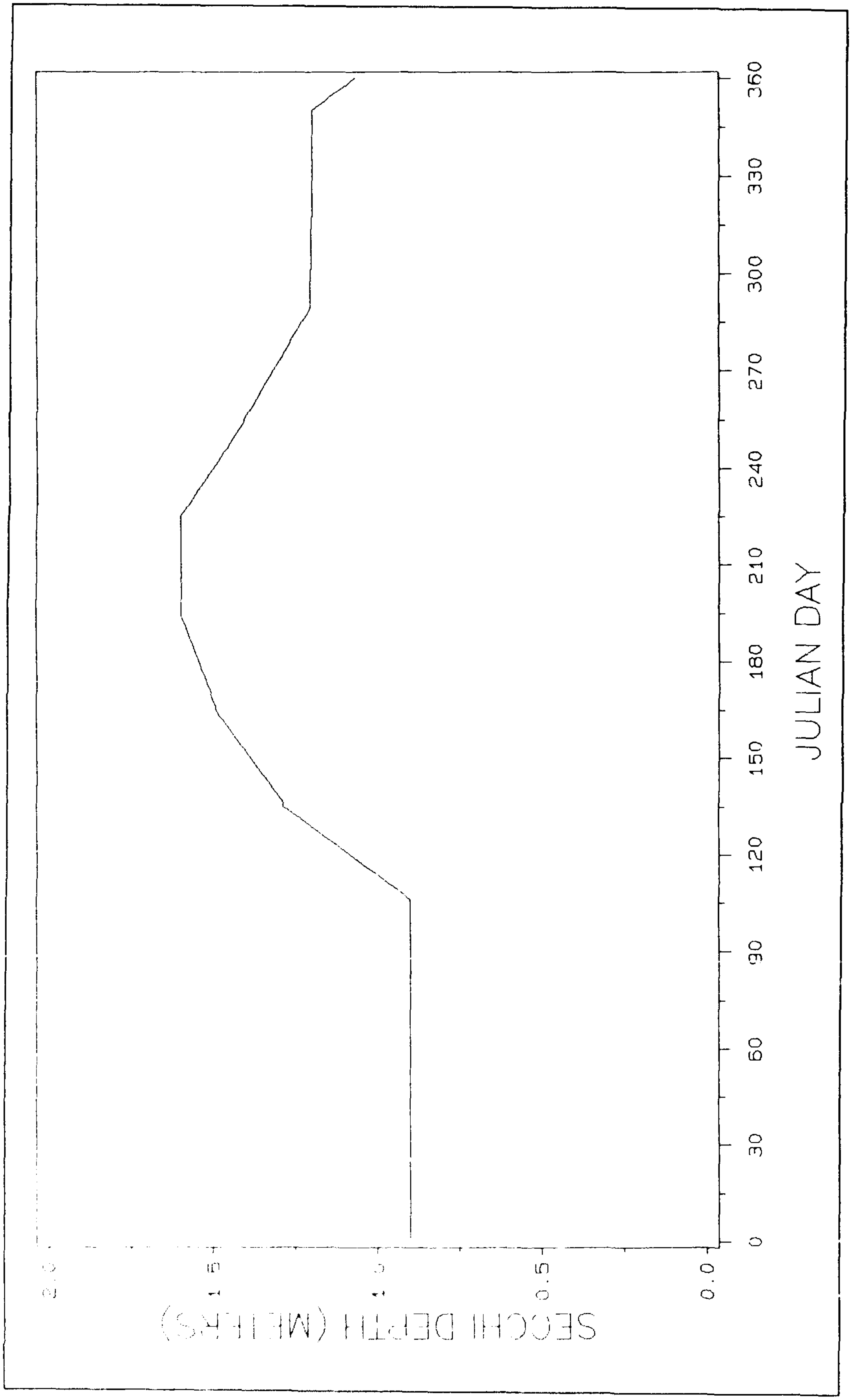


Figure 4. Secchi disk depth readings for the Chisenhall site, Guntersville Reservoir. (Derived from interpolating between monthly readings at the site on sampling dates listed in Table 1)

means. As illustrated in Figure 5, the plant biomass estimates from the MILFOIL model, which are represented by the solid line, compare well with estimates from the field study. MILFOIL model-derived estimates are well within the confidence intervals of six of the seven monthly field estimates. Model-generated estimates were extremely close to field estimates during the spring regrowth period, and estimates of peak biomass during summer months were comparable.

Planned studies

During fiscal year 1991, additional field data sets will be collected at Guntersville Reservoir for further comparison with MILFOIL model simulation results. Additionally, field estimates for biomass levels in hydrilla colonies in Guntersville Reservoir will be determined and compared with HYDRILLA model simulation results. Our current environmental and meteorological database will be improved to allow more proper initialization of these models for Guntersville Reservoir conditions.

References

Akbay, K. S., Wooten, J. W., and Howell, F. G. 1988. Simulation model of waterhyacinth and its biocontrol agents; Report 1, First-generation model. Technical Report A-88-8. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sabol, B. M. 1984. Development and use of the Waterways Experiment Station's hydraulically operated submersed aquatic plant sampler. Pages 46-57 in Ecological Assessment of Macrophyton: Collection, Use, and Meaning of Data. W. M. Dennis and B. G. Isom, eds. Special Technical Publication 843. American Society for Testing and Materials, Philadelphia, PA.

Wooten, J. W. 1989. Description and update: An improved hydrilla growth model. Pages 283-289 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wooten, J. W. 1990. Plant growth simulation models for hydrilla and Eurasian watermilfoil. Pages 240-246 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program*. Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

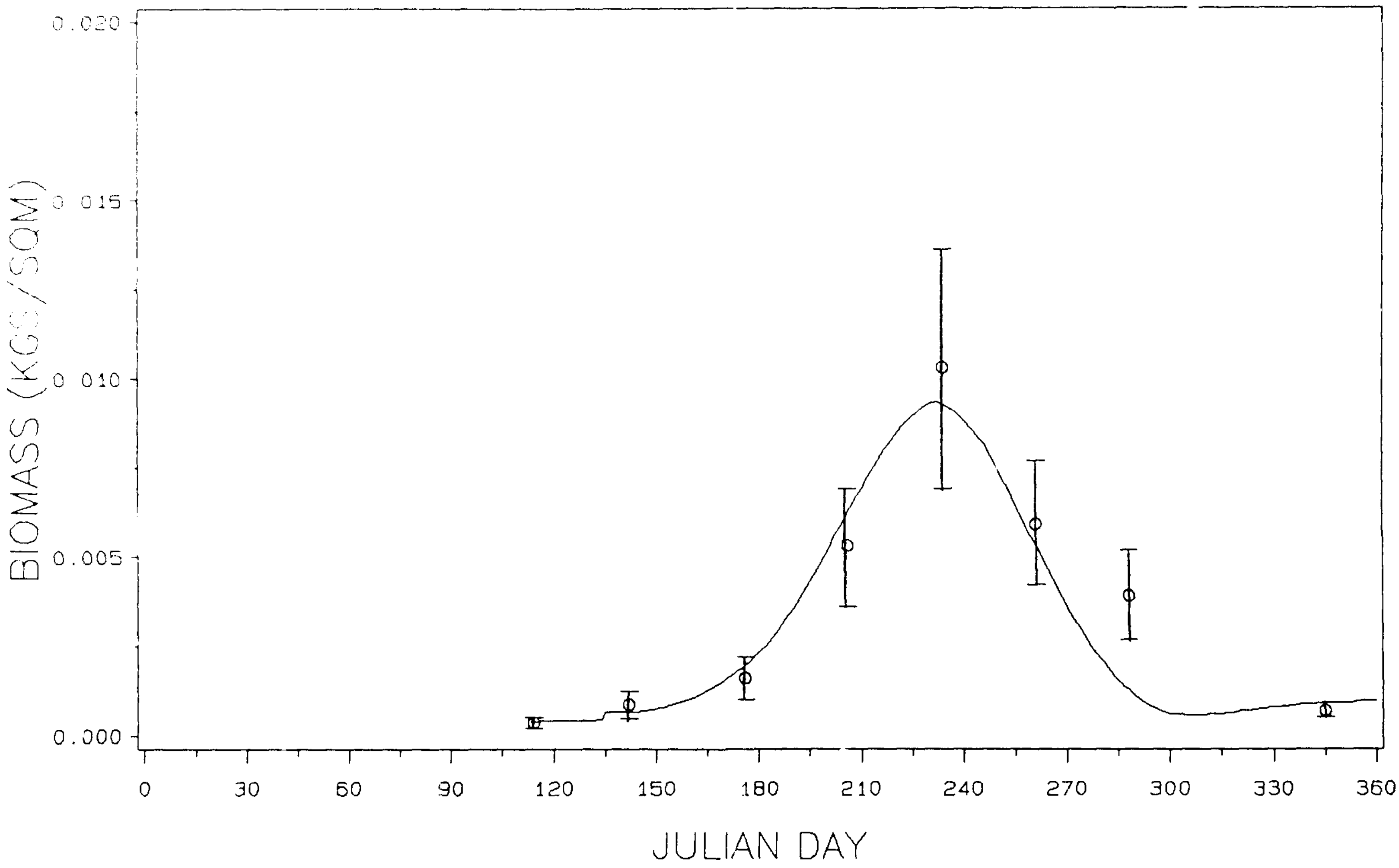


Figure 5. Comparison of simulation results (solid line) for Eurasian watermilfoil dry weight biomass from the MILFOIL model with the 1990 field data from Chisenhall site, Guntersville Reservoir. Field data are plotted as means (circles) and 95-percent confidence intervals (vertical lines) calculated using the T-distribution ($T_{0.025,24}$). Dry weight estimates for field samples were calculated as 10 percent of fresh plant sample weights after a 6-min spin cycle in a washing machine

Biocontrol Simulations

by
William A. Boyd[1] *and R. Michael Stewart*[1]

Introduction

Aquatic plant infestations can cause significant problems with the intended use of many of the Nation's waterways. Several methods are now available to control aquatic plants, including mechanical, chemical, and biological techniques. Of these three broad categories of aquatic plant control methods, biological control techniques are perhaps the most difficult to effectively apply because these techniques rely on the action of a biological agent.

Proper application of biocontrol techniques can be made easier by the use of computer-aided biocontrol simulation models. Two computer-based biocontrol simulation models, which contain plant growth and biological control agent algorithms, have been developed by the Waterways Experiment Station (WES) to help aquatic plant managers determine proper applications/use of biological control techniques.

One of these models, INSECT Version 1.0, simulates interactions between waterhyacinth plants (*Eichhornia crassipes*) and *Neochetina* weevils; the other, AMUR/STOCK Version 1.5, simulates the growth of white amur fish and the impacts the fish will have on target plants (e.g., hydrilla and Eurasian watermilfoil). INSECT is described in detail by Akbay, Wooten, and Howell 1988), and updates to the model are described in Howell, Akbay, and Stewart (1988) and Howell and Stewart (1989).

This paper gives a brief description of the AMUR/STOCK (Version 1.5) model and presents preliminary AMUR/STOCK simulation results for Guntersville Reservoir, Alabama.

Description of AMUR/STOCK (Version 1.5)

The AMUR/STOCK model was developed to provide users with a computer-based, systematic evaluation tool for answering "what if" questions regarding the impacts to target plant infestations resulting from different white amur stocking strategies.

In this context, stocking strategies to be evaluated by the AMUR/STOCK model may differ by the size of white amur stocked, the number of fish stocked, the number of times fish are stocked, the species of aquatic plants present, the acreage of each aquatic plant's infestation, the maximum seasonal density (tons per acre) of the plant(s), the annual water temperature regime of the water body, or the time period for the simulation.

An earlier version of the AMUR/STOCK model (Miller and Decell 1984) used several basic relationships to simulate the growth of hydrilla and the consumption of hydrilla by white amur, over a user-specified period of time. Hydrilla growth for the period was calculated as a function of the previous month's standing crop and a growth rate factor for the current month.

The growth rate factor was determined using relationships for season, water temperature, photoperiod, water body carrying capacity for hydrilla, and hydrilla cropping by white amur. By selecting proper input values, the user could generate hydrilla plant growth simulations for the particular environmental conditions of the water body being considered.

---

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

The AMUR/STOCK (Version 1.5) model (Boyd and Stewart 1990) includes two additional sets of relationships for season, water temperature, photoperiod, water body carrying capacity, and plant cropping that have been developed for calculating growth rates of Eurasian watermilfoil and a complex of annual species found in Guntersville Reservoir. These relationships were established for the Guntersville Reservoir conditions using seasonal plant biomass data for these species as reported by the Tennessee Valley Authority (1983, 1987, 1989).

In addition, new relationships were established for fish feeding and growth in the AMUR/STOCK model to expand the applicability of the model for white amur genetic variants other than diploids, and to plant species other than hydrilla. In general, these relationships incorporate the white amur feeding, growth, and mortality relationships included in the Illinois Herbivorous Fish Simulation System, as reported in Wiley and Gorden 1985, Wiley et al. (1985), and Wiley and Wike (1986).

AMUR/STOCK Simulation Results for Guntersville Reservoir

In 1989 the Tennessee Valley Authority (TVA) asked WES to assist them in determining a stocking rate of triploid white amur that would support TVA's long-range aquatic plant management objective for Guntersville Reservoir. Guntersville Reservoir is a 68,000-acre TVA-managed reservoir on the Tennessee River. The TVA aquatic plant management objective included gradually reducing the aquatic plant infestation level from the 20,000 acres reported in 1988 to approximately 6,800 acres, or 10 percent of the reservoir surface area. Control below 3,400 acres, or 5 percent of the reservoir surface area, was not desired.

Boyd and Stewart (1990) presented results of several simulation scenarios that were generated in response to TVA's 1989 request. All simulation results reported therein, which were generated using "prestocking" plant infestation levels approximating those reported for 1988, indicated that a minimum of 200,000 fish would be required to achieve TVA's aquatic plant management objectives. Boyd and Stewart (1990) recommended that 1988 estimates of aquatic plant infestation levels be confirmed during the following years to help validate prestocking conditions.

Aerial surveys conducted by TVA during the fall of 1989 and 1990 indicated that dramatic reductions in the plant infestation levels occurred. Field studies conducted during 1990 by TVA and WES have provided better estimates for plant biomass levels in infested areas. Based on these measurements, additional simulations were generated for plant infestation levels reported for 1989 and 1990.

For these simulations, the AMUR/STOCK model was initialized with a water temperature data file (Figure 1) that represented the average median monthly water temperature measurements from Nickajack Dam tailrace during the period 1984 through 1987 (TVA, unpublished data).

The following paragraphs summarize the model initialization conditions and simulation results for a 1989 simulation scenario and a 1990 simulation scenario. The model initialization conditions included the following information: (a) infested acreage by plant species, (b) estimates of maximum seasonal fresh weight biomass by plant species, (c) number and size of white amur stocked, and (d) month of stocking.

Simulation results are presented for the following: (a) monthly standing crop estimates for each plant species over a 1-year simulation period without impacts from white amur, (b) the highest monthly standing crop estimate for each plant species and for all species combined without impacts from white amur, and (c) the highest monthly combined standing crop estimates for each year of a 10-year simulation period with impacts from white amur.

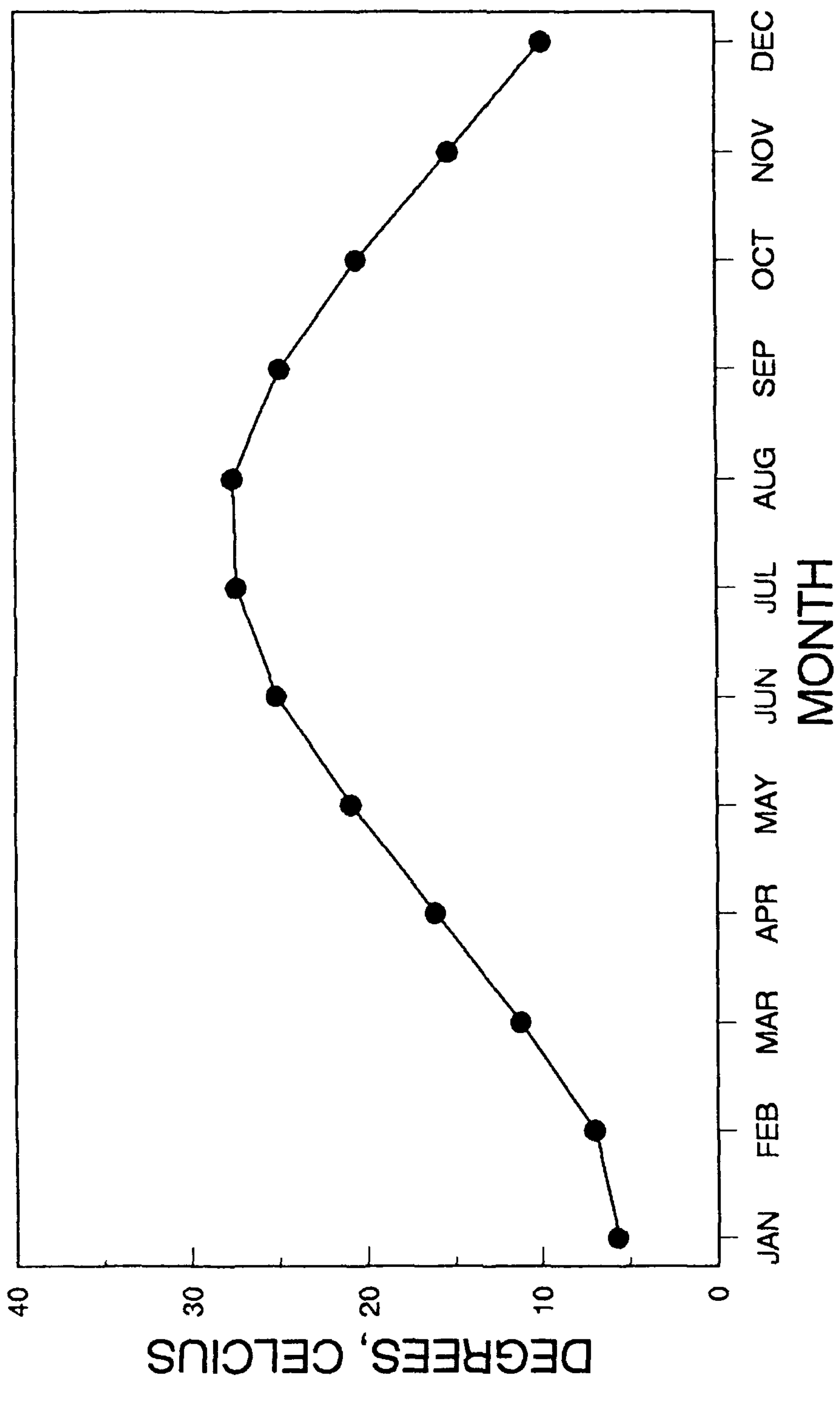


Figure 1. Average median monthly water temperatures from measurements made by TVA at Nickajack Dam tailrace, 1984-87

Simulation results for 1989 conditions

Monthly plant standing crop estimates for a 1-year period under 1989 aquatic plant infestation levels (Table 1) are shown in Figure 2. These plant growth simulations do not include impact (feeding) from white amur stockings. As shown in Figure 2, plant standing crop estimates of all three plant species were highest during June through August. Figure 3 summarizes the highest estimates and shows that the highest combined standing crop for all three species was 123,700 tons.

Table 1
Simulation Conditions for 1989 Conditions

Infested Area		
Plant Species	**Acreage**	
Eurasian watermilfoil	11,000	
Hydrilla	2,000	
Annual species	1,000	
Maximum Seasonal Biomass		
Plant Species	**Tons/Acre**	
Eurasian watermilfoil	7.1	
Hydrilla	20.0	
Annual species	5.6	
White Amur Stocked		
Stocking Time	**Number Stocked**	**Avg Size**
May, Year 1	35,000	0.75 lb
June, Year 1	50,000	0.75 lb
July, Year 1	15,000	0.75 lb

The standing crop simulations presented in Figure 4 are the combined maximum monthly plant weight estimates for all plant species for each year over a 10-year period. Input conditions were identical to Table 1 conditions used to generate simulations summarized in Figure 3, except that these estimates include multiple white amur stockings of 35,000 fish in May, 50,000 in June, and 15,000 in July during Year 1 of the simulation period. All fish were assumed to weigh 0.75 lb at the time of stocking. The proportion of fish used in the separate simulations for each plant species is shown in Table 2.

Based on plant preference and availability assumptions, the stocked fish were assumed to be equally distributed between the annuals and hydrilla during Year 1. As fewer fish were required for complete control of the annuals during Year 2, a larger proportion of the fish fed on hydrilla. The assumption was made that the annuals would not produce significant regrowth following 2 years of heavy feeding pressure, and therefore would not be available for the fish to feed on after Year 2. In Year 3, about 80 percent of the fish remaining were needed to effectively control hydrilla, and the remaining 20 percent fed on Eurasian watermilfoil.

The proportion of fish feeding on hydrilla gradually declined each year until Year 6, when about 50 percent of the fish were needed to effectively control hydrilla. The proportions remained the same until Year 10, when 67 percent of the fish were needed to control hydrilla. The increase in the proportion of fish needed to control hydrilla in Year 10 was due to fish mortality. As fewer fish were present, a greater proportion was needed to control hydrilla. Consequently, the level of control exerted by the fish on Eurasian watermilfoil was reduced during Year 10.

Table 2
Assumed Proportions of Fish Feeding on Each Plant Type During Each Year of Simulations for 1989 Conditions

Plant Type	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
Annuals	.50	.11	.00	.00	.00	.00	.00	.00	.00	.00
Hydrilla	.50	.89	78	.60	.55	.52	.52	.52	.52	.67
Milfoil	.00	.00	.22	.40	.45	.48	.48	.48	.48	.33

Based on the set of input conditions and assumptions for 1989, simulation results showed control of the annuals at the end of Year 1 and of the hydrilla at the end of Year 2 (see Figure 4). The stocked fish then produced a gradual decline in the Eurasian watermilfoil standing

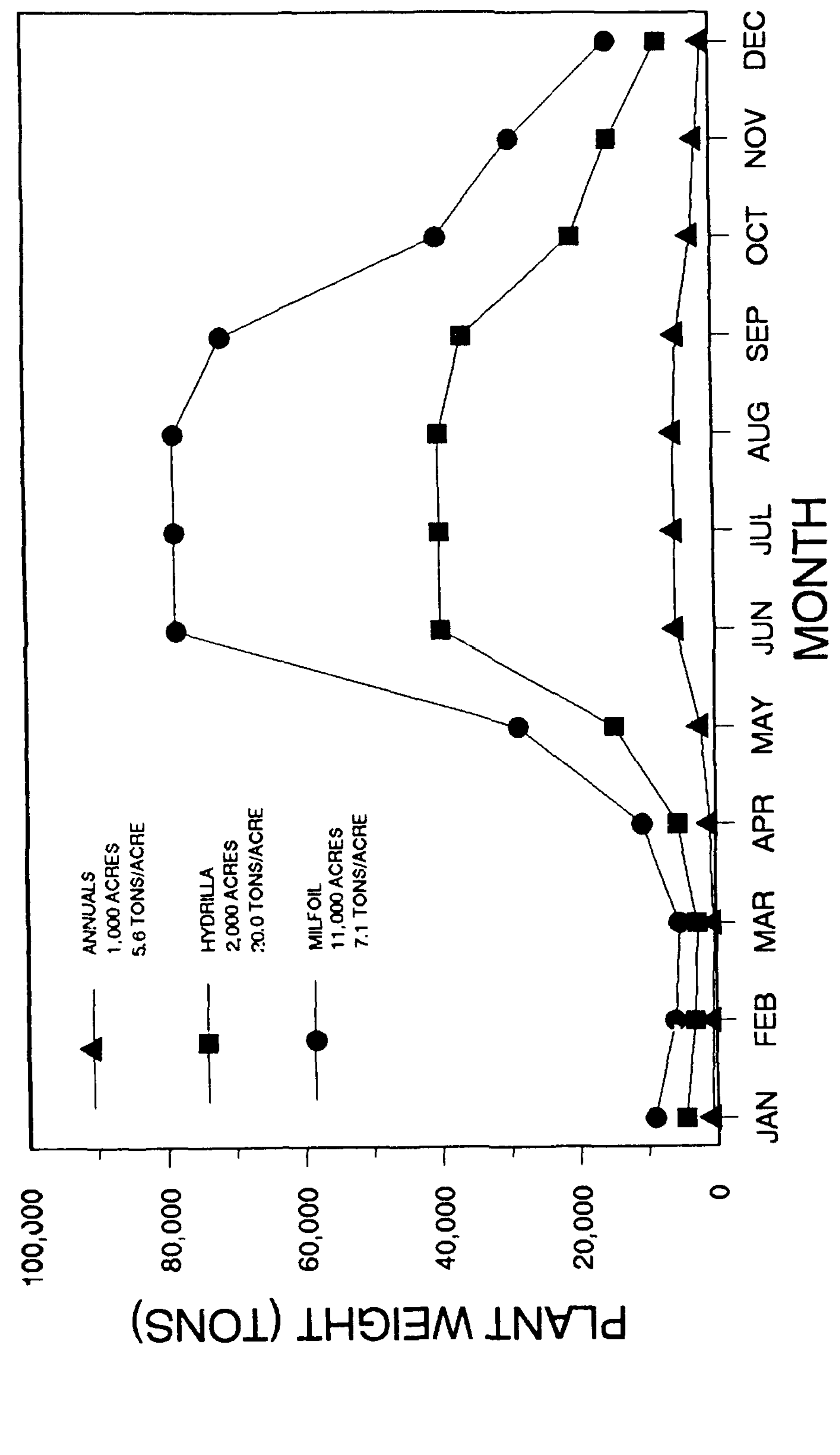


Figure 2. Monthly standing crop estimates for each plant species under 1989 aquatic plant infestation levels without white amur stockings

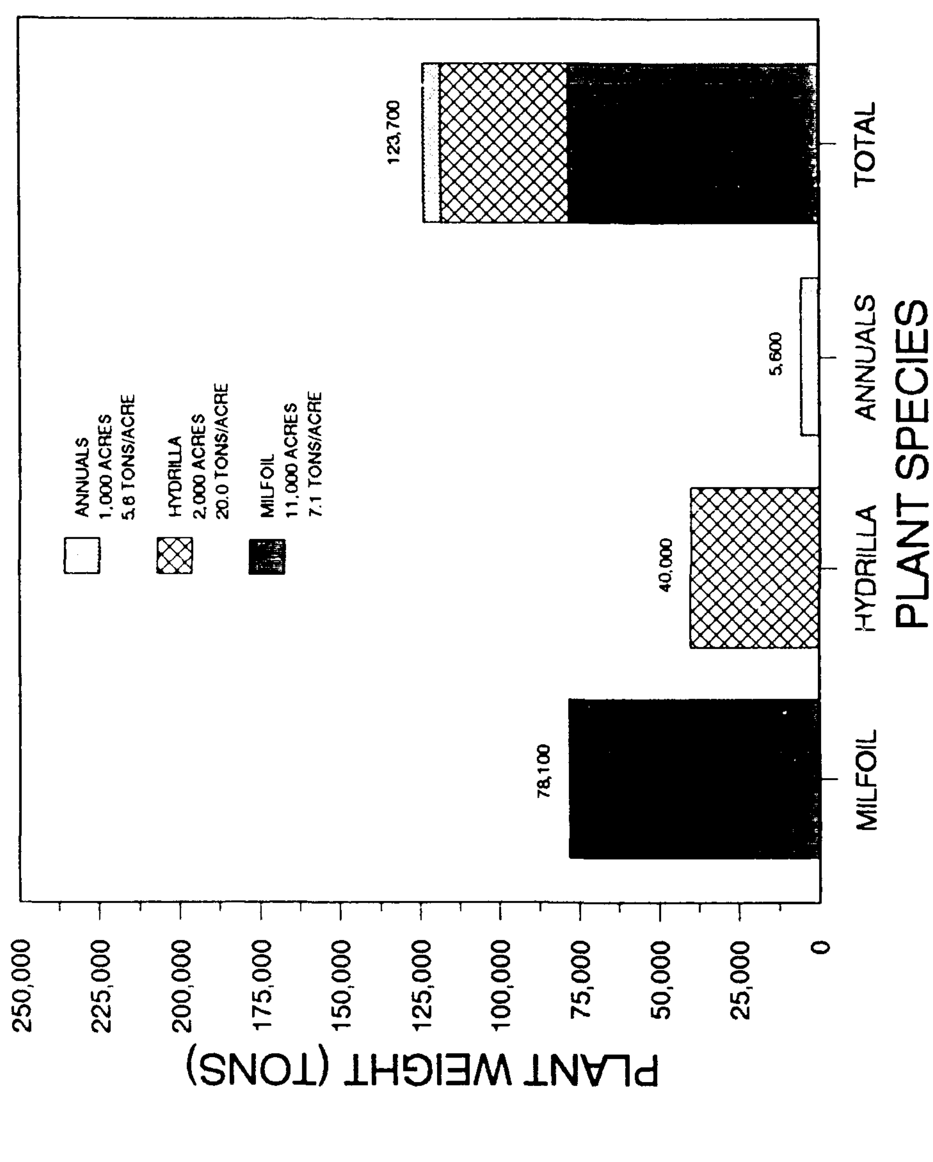


Figure 3. Highest monthly standing crop estimates (for each plant species and for all species combined) under 1989 aquatic plant infestation levels without white amur stockings

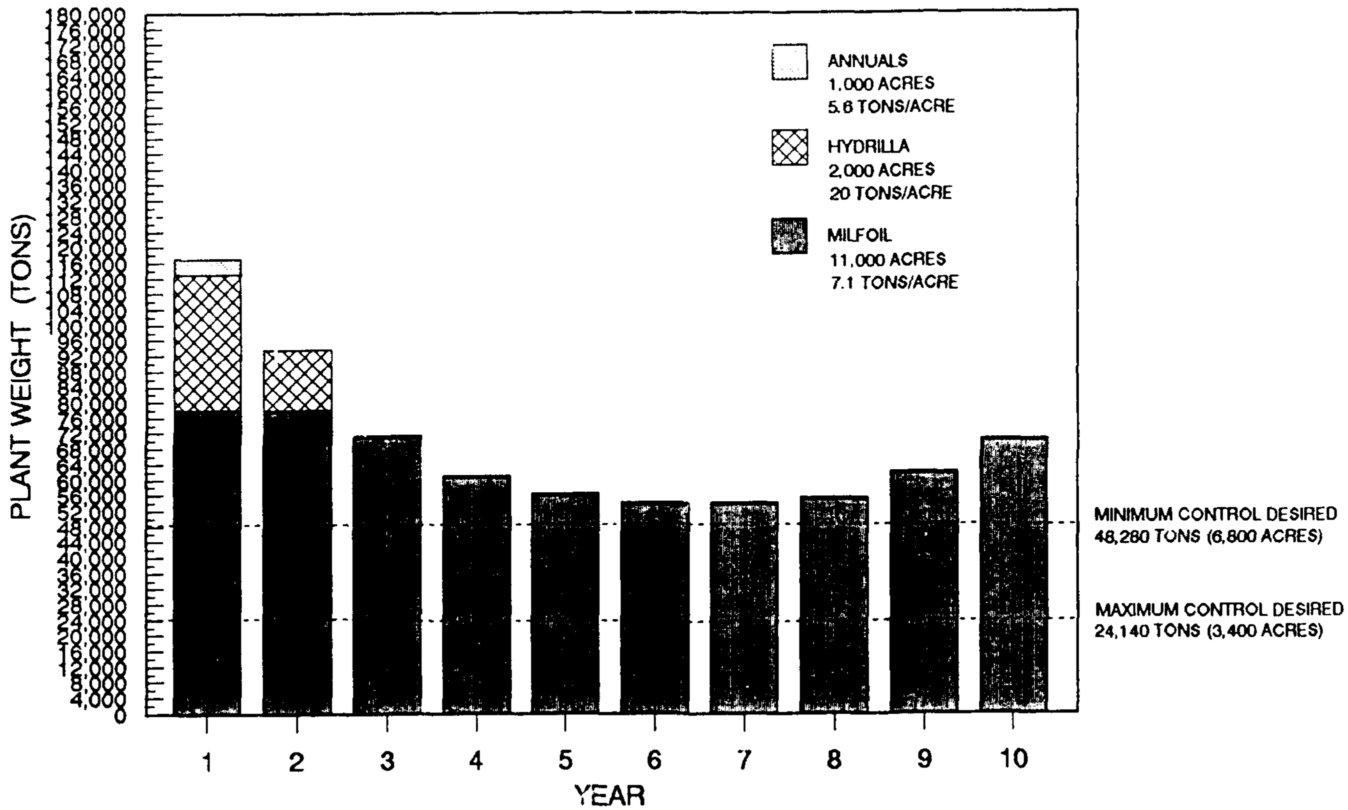


Figure 4. Peak annual standing crop estimates from a set of 10-year simulations conducted under 1989 aquatic plant infestation levels with white amur stockings (35,000 fish in May, 50,000 in June, and 15,000 in July of Year 1). See text for assumptions made regarding fish feeding. Dashed lines mark upper and lower limits of the maintenance infestation level desired by TVA. These levels represent the product of 5 and 10 percent of the reservoir being infested at maximum standing crop levels for milfoil

crop. By Year 6 of the 10-year simulation period, the combined standing crop of all species was brought near the desired control level of 48,280 tons. Because of fish mortality, however, the combined plant standing crop began to increase in Year 8, and increased to approximately 72,000 tons in Year 10 (see Figure 4).

Simulation results for 1990 conditions

Monthly plant standing crop weight estimates for a 1-year period under 1990 plant infestation levels (Table 3) are shown in Figure 5. These plant growth simulations do not include impacts (feeding) from white amur stockings. As shown in Figure 5, plant standing crop estimates of all three species were highest during the months of June through August. Figure 6 summarizes the highest estimates and shows that the highest combined standing crop for all three species was 95,300 tons.

Table 3
Simulation Conditions for 1990 Conditions

Infested Area		
Plant Species	**Acreage**	
Eurasian watermilfoil	7,000	
Hydrilla	2,000	
Annual species	1,000	
Maximum Seasonal Biomass		
Plant Species	**Tons/Acre**	
Eurasian watermilfoil	7.1	
Hydrilla	20.0	
Annual species	5.6	
White Amur Stocked		
Stocking Time	**Number Stocked**	**Avg Size**
May, Year 1	35,000	0.75 lb
June, Year 1	50,000	0.75 lb
July, Year 1	15,000	0.75 lb

The standing crop estimates presented in Figure 7 are the combined maximum monthly weight estimates for all plant species for each year over a 10-year period. Input conditions are given in Table 3 and were used to generate simulations summarized in Figure 6, except that these estimates include multiple white amur stockings of 35,000 fish in May, 50,000 in June, and 15,000 in July during Year 1 of the simulation period. All fish were assumed to weigh 0.75 lb at the time of stocking. The proportion of fish used in the separate simulations for each plant species is shown in Table 4.

Based on plant preference and availability assumptions, the stocked fish were assumed to be equally distributed between the annuals and hydrilla during Year 1. Fewer fish were required for complete control of the annuals during Year 2; thus, almost 90 percent were assumed to feed on hydrilla. The assumption was made that the annuals would not produce significant regrowth following 2 years of heavy feeding pressure, and therefore would not be available for the fish to feed on after Year 2. In Year 3, over 75 percent of the fish remaining were needed to effectively control hydrilla, and the remaining fish fed on Eurasian watermilfoil.

The proportion of fish feeding on hydrilla gradually declined each year until Year 6, when about 50 percent of the fish were needed to effectively control hydrilla. The proportions remained the same until Year 10, when 67 percent of the fish were needed to control hydrilla. The increase in the proportion of fish needed to control hydrilla in Year 10 was a result of fish mortality, as discussed for the simulation results for 1989 conditions.

Based on the set of input conditions and assumptions for 1990, the simulation results showed control of the annuals at the end of

Table 4
Assumed Proportions of Fish Feeding on Each Plant Type During Each Year of Simulations for 1990 Conditions

Plant Type	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
Annuals	.50	.11	.00	.00	.00	.00	.00	.00	.00	.00
Hydrilla	.50	.89	.78	.60	.55	.52	.52	.52	.52	.67
Milfoil	.00	.00	.22	.40	.45	.48	.48	.48	.48	.33

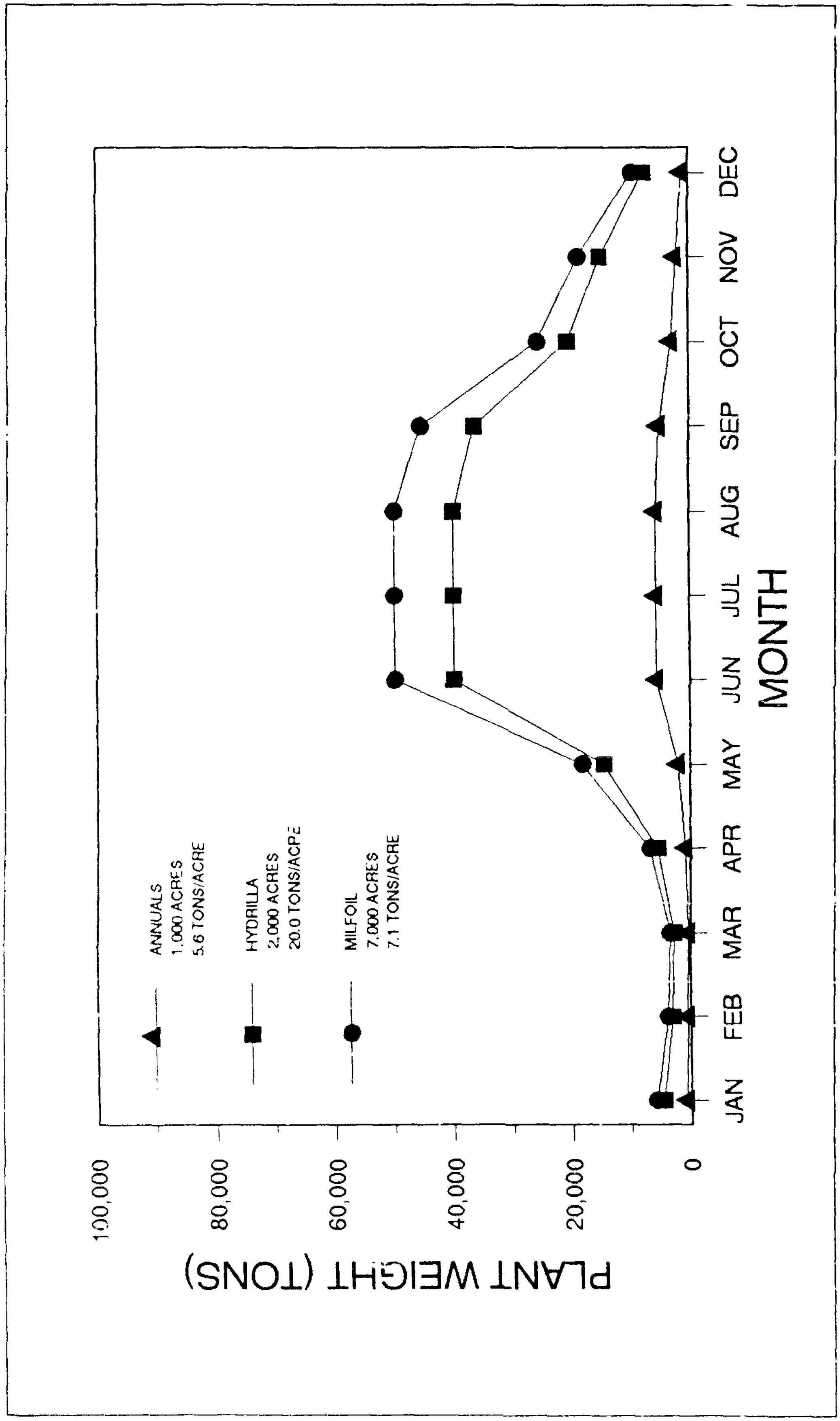
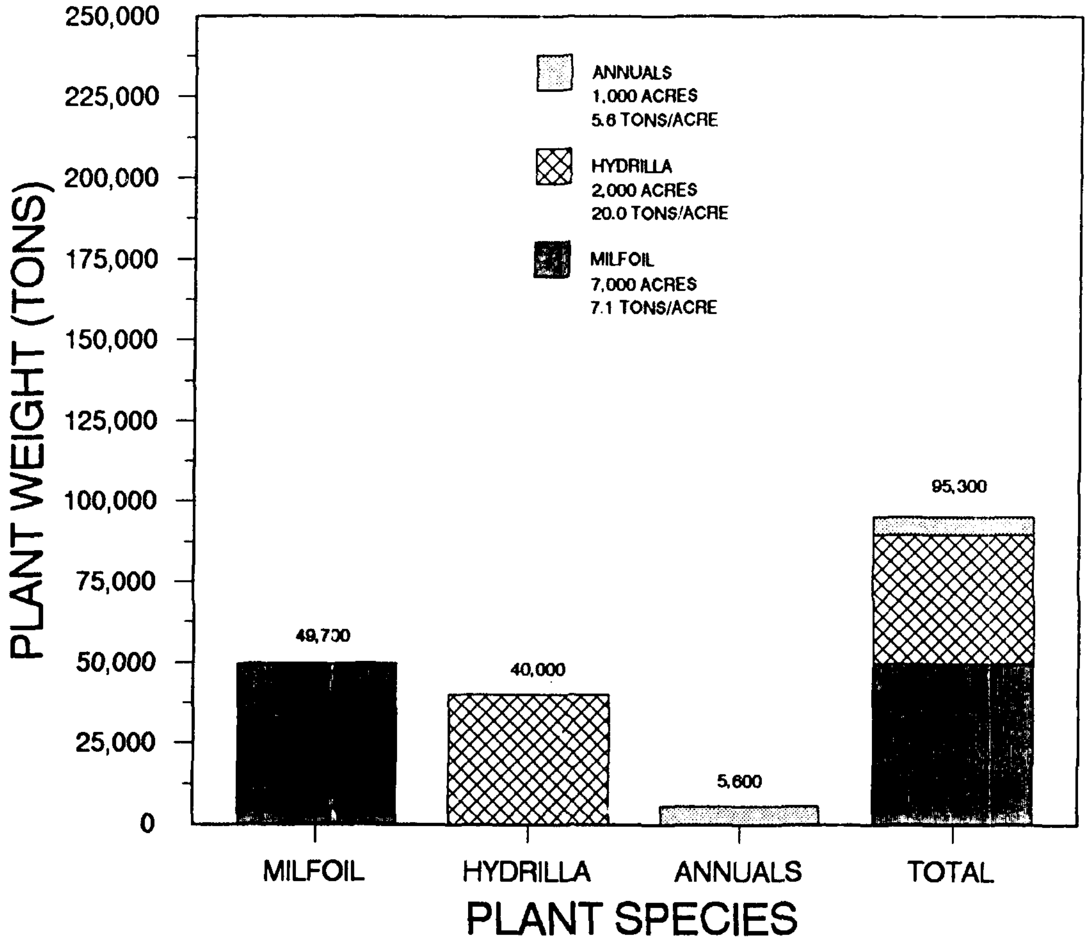


Figure 5. Monthly standing crop estimates for each plant species under 1990 aquatic plant infestation levels without white amur stockings



Figues 6. Highest monthly standing crop estimates (for each plant species and for all species combined) under 1990 aquatic plant infestation levels without white amur stockings

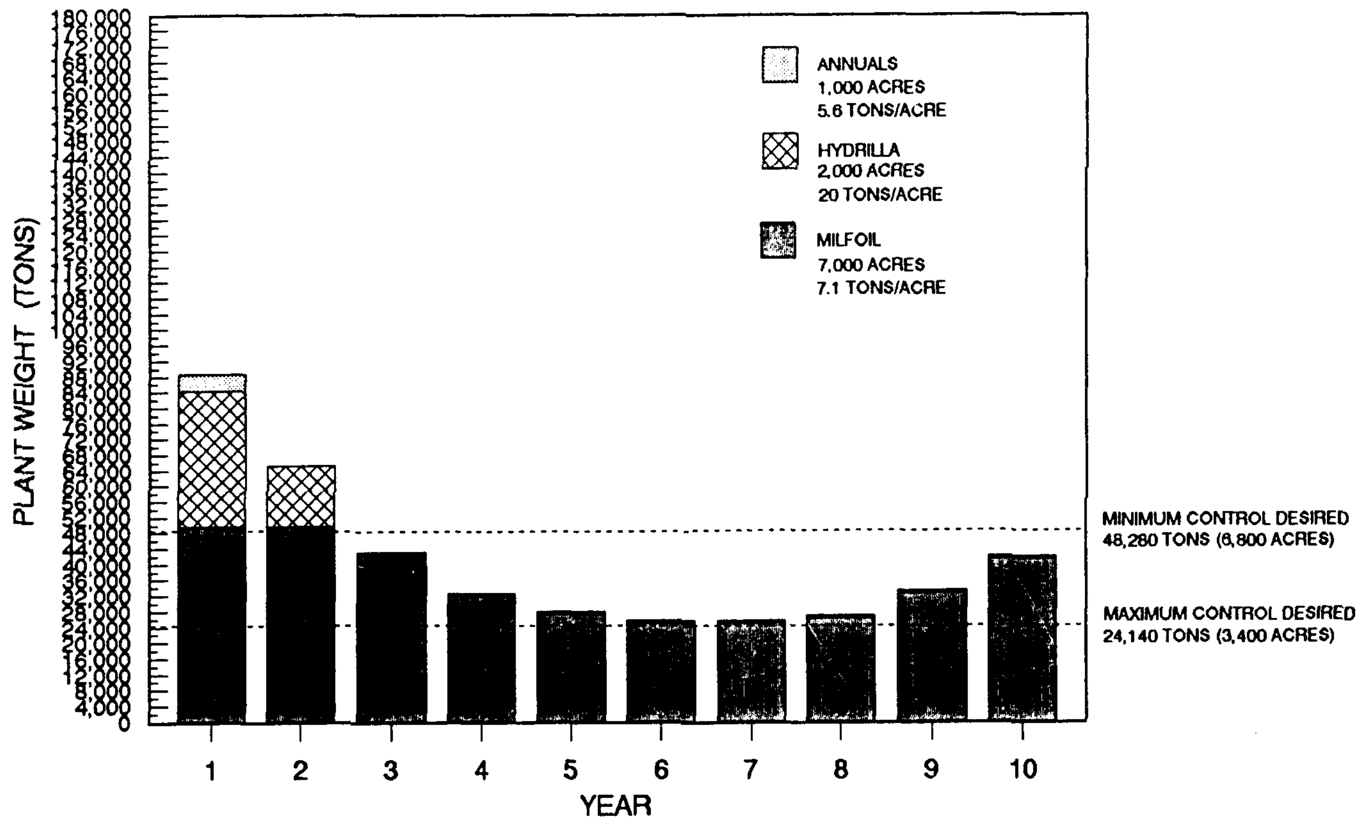


Figure 7. Peak annual standing crop estimates from a set of 10- year simulations conducted under 1990 aquatic plant infestation levels with white amur stockings (35,000 fish in May, 50,000 in June, and 15,000 in July of Year 1). See text for assumptions made regarding fish feeding. Dashed lines mark upper and lower limits of the maintenance infestation level desired by TVA. These levels represent the product of 5 and 10 percent of the reservoir being infested at maximum standing crop levels for milfoil

Year 1 and of hydrilla at the end of Year 2. By Year 3 of the 10-year period, the combined standing crop of all species was slightly below the desired level of control, 48,280 tons (6,800 acres). During following years, through Year 8, the plant standing crop was reduced to a level near the maximum desired control level of 24,140 tons (3,400 acres). During Years 9 and 10, the plant infestations increased but still remained below the desired level of control (48,280 tons or 6,800 acres).

Discussion

Simulation results reported in Boyd and Stewart (1990) and herein were generated using "prestocking" conditions approximating 1988, 1989, and 1990 Guntersville Reservoir aquatic plant infestation levels as reported by TVA. However, plant infestation levels in Guntersville Reservoir have declined from 20,000 acres in 1988 to 10,000 acres in 1990.

Simulation results reported in Boyd and Stewart (1990) for 1988 prestocking conditions indicated that a minimum of 200,000 fish would be required to achieve the level of aquatic plant control desired by TVA. In comparison, simulation results reported herein for 1989 prestocking conditions indicate that only 100,000 fish will be required to achieve the level of control desired by TVA. Further, results of simulations based on 1990 prestocking conditions indicate that 100,000 fish will achieve control below TVA's desired level.

The simulation results discussed above indicate that stocked fish will impact their greatest levels of control during poststocking years 5 through 7. Therefore, the 100,000 fish stocked in Guntersville Reservoir by TVA in 1990 will possibly not effect their greatest level of control before 1994. Actual levels of control achieved will depend on the status of environmental factors that have been responsible for the observed changes in plant infestation levels during 1988 through 1990.

Because it is impossible to predict the effect that these other environmental factors will have on plant infestation levels over the next several years, it is recommended that no additional white amur stockings be made before 1995.

References

Akbay, K. S., Wooten, J. W., and Howell, F. G. 1988. Simulation model of waterhyacinth and its biocontrol agents; Report 1, First-generation model. Technical Report A-88-8. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Boyd, W. A., and Stewart, R. M. 1990. Preliminary simulation results of triploid white amur stocking rates at Guntersville Reservoir using AMUR/STOCK (Version 1.5). Pages 247-260 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Howell, F. G., Akbay, K. S., and Stewart, R. M. 1988. Field validation and improvements to INSECT, a personal computer simulation model. Pages 160-168 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Howell, F. G., and Stewart, R. M. 1989. Application of INSECT, a computer model of waterhyacinth and *Neochetina* population dynamics. *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, A. C., and Decell, J. L. 1984. Use of the white amur for aquatic plant management. Instruction Report A-84-1. US

Army Engineer Waterways Experiment Station, Vicksburg, MS.

Tennessee Valley Authority. 1983. First preoperational assessment of water quality and biological resources of Guntersville Reservoir in the vicinity of the proposed Murphy Hill Coal Gasification Project. TVA/ORN/WRF-83-2. Office of Natural Resources, Knoxville, TN.

Tennessee Valley Authority. 1987. White amur project. TVA/ONRED/AWR-87/38. Office of Natural Resources and Economic Development, Muscle Shoals, AL.

Tennessee Valley Authority. 1989. Supplement to white amur project. TVA/WR/AB-89/1. Water Resources, Muscle Shoals, AL.

Wiley, M. J., and Gorden, R. W. 1985. Biological control of aquatic macrophytes by herbivorous carp; Part II, Biology and ecology of herbivorous carp. Aquatic Biology Technical Report 1984(11). Illinois Natural History Survey, Champaign, IL.

Wiley, M. J., Tazik, P. P., Sobaski, S. T., and Gorden, R. W. 1985. Biological control of aquatic macrophytes by herbivorous carp; Part III, Stocking recommendations for herbivorous carp and description of the Illinois Herbivorous Fish Simulation System. Aquatic Biology Technical Report 1984(12). Illinois Natural History Survey, Champaign, IL.

Wiley, M. J., and Wike, L. D. 1986. Energy balances of diploid, triploid, and hybrid grass carp. *Transactions of the American Fisheries Society* 115:853-863.

Enhancement of HERBICIDE, the Aquatic Herbicide Fate and Effects Model

by
John H. Rodgers, Jr.,[1] *Philip A. Clifford,*[2] *and R. Michael Stewart*[3]

Background

The level of control obtained from a herbicide application on a target aquatic plant infestation is driven by the time-varying concentration of the herbicide following application and by herbicide exposure and plant mortality relationships unique for each combination of herbicide and target plant. Current research being conducted by the Chemical Control Technology team of the Aquatic Plant Control Research Program (APCRP) is focusing on development of these exposure/mortality relationships for a series of target aquatic plant and herbicide combinations (Netherland 1990).

Direct application of these basic relationships requires determination of the effects of site-specific fate processes on time-varying concentrations of the herbicide following application. Though water transport is certainly a major factor driving transfer of a herbicide from the application site (Netherland 1990), other transfer and transformation processes (Reinert and Rodgers 1987) are often important in determining the site-specific fate of a herbicide.

HERBICIDE is a personal computer-based software package designed to generate simulation results for fate and effects of aquatic herbicides. HERBICIDE simulation results can assist aquatic plant managers in the design of site-specific herbicide application strategies that are based on field- and laboratory-derived herbicide exposure and plant mortality relationships.

The fate portion of the simulation program (Module I) focuses on transfer and transformation of a herbicide after introduction into an aquatic system for control of nuisance aquatic plants. This module contains a series of linear or nonlinear differential equations that are designed to calculate the mass balance through time of herbicide in an aquatic system.

The mass balance equation considers such physical factors as dilution and dispersion, drift and interception, as well as volatilization, photolysis, hydrolysis, and sorption. Also included are first-order biotransformation rates for each herbicide. Uptake and depuration, which drive plant tissue concentrations of herbicide, are also included. The outputs from the fate module (i.e., time-integrated concentrations of herbicide in water, sediments, and plant tissues) are used as inputs to the exposure-response module.

The exposure-response module (Module II) generates a simulation of the toxicological responses of the target aquatic plant infestation to the herbicide exposure estimated by Module I. This includes laboratory- or field-determined relationships for response or mortality of a target aquatic plant population to a given exposure of a specific herbicide. Included are the minimum tissue burdens that must be achieved to elicit a measureable plant response and the upper threshold concentrations of the herbicide that essentially saturate the response of the target plant and achieve maximum mortality.

[1] Department of Biology, Biological Field Station, University of Mississippi, University, MS.
[2] EA Engineering, Science, and Technology, Inc., Mid-Atlantic Operations, Sparks, MD.
[3] US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Module III simulates the response, or regrowth, of the target plant infestation following herbicide application. Module III is based on existing plant growth simulation models developed for the APCRP (Wooten and Stewart 1991).

Previous development efforts of the HERBICIDE model focused on relationships for dimethylamine salt formulations of 2,4-dichlorophenoxyacetic acid (2,4-D DMA) and waterhyacinth. These prior development efforts are described by Rodgers, Clifford, and Stewart (1988) and Clifford, Rodgers, and Stewart (1989, 1990). These descriptions include the conceptual design of the HERBICIDE model, parameterization of the fate and effects algorithms and development of support databases for 2,4-D (DMA) applications to waterhyacinth, and laboratory and field validation studies.

Fiscal Year 1990 Accomplishments

Additional HERBICIDE fate and effects relationships

Although the HERBICIDE model was initially calibrated and validated for simulating applications of 2,4-D for control of waterhyacinth, the model was designed to allow easy expansion for other combinations of target aquatic plants and herbicides. During FY 90, modifications and improvements to the software package have included addition of algorithms and supporting data for the following combinations:

- Waterhyacinth and diquat (liquid).
- Eurasian watermilfoil and fluridone (Sonar SRP) (granular).
- Eurasian watermilfoil and 2,4-D (BEE) (granular).
- Eurasian watermilfoil and endothall (Aquathol) (granular).
- Eurasian watermilfoil and diquat (liquid).
- Hydrilla and endothall (Aquathol K) (liquid).
- Hydrilla and diquat (liquid).

Modifications to fate algorithms

Two significant modifications were made to Module I fate algorithms. The first was inclusion and calibration of an algorithm designed to simulate release of herbicide active ingredients from granular formulations. The original model, which was developed and calibrated for simulation of aerial spray-applied 2,4-D (DMA), assumed instantaneous mixing (equilibrium) of the nonintercepted spray with water. This was satisfactory since waterhyacinths were demonstrated to receive the majority of herbicide exposure from interception of aerial spray and not from aqueous exposure.

For submersed aquatic plants that receive the majority of exposure from aqueous concentrations of herbicide, more accurate measures of herbicide concentrations in water are required. Since granular formulations release herbicide to water in a nonlinear manner, a new algorithm was developed to simulate observed release of herbicides (i.e. endothall and fluridone) from solid matrices as reported in the literature (Reinert et al. 1985 and unpublished data). This allows essentially nonequilibrium estimation of concentrations of herbicides within water, sediment, and plant tissues.

The second major modification to fate algorithms involves the route of herbicide uptake into plant tissues. In the original model, the route of 2,4-D uptake by waterhyacinth was linked to an algorithm which accounted for "interception" of the aerial spray-applied liquid formulation by emergent plant tissues, as discussed above. Since Eurasian watermilfoil and hydrilla are submergent plants and are not exposed to herbicides in the same

manner as waterhyacinth, modifications were made such that the route of uptake is via aqueous exposure rather than via interception for these target plant species.

Modifications to HERBICIDE effects algorithms

The exposure-mortality response algorithm (Module II) included in the original model was fitted to a power curve determined to be appropriate for 2,4-D (DMA) and waterhyacinth, as demonstrated in validation experiments (Clifford, Rodgers, and Stewart 1990). This unusual exposure-response relationship is most likely the result of the unique action of 2,4-D on waterhyacinth.

Because other target plant and herbicide combinations added during FY 90 were not expected to exhibit this type of exposure-mortality response relationship, a revised exposure-mortality response algorithm was added that produces a more classical sigmoidal type of response. This algorithm was calibrated based on literature data for the various combinations of herbicides and target plants added during FY90.

Additions to supporting databases

As described by Rodgers, Clifford, and Stewart (1988) and Clifford, Rodgers, and Stewart (1989, 1990), the HERBICIDE software package includes a series of default data sets needed for calibrating the fate and effects algorithms for the particular herbicide and target plant combination under investigation. Therefore, separate default data sets were developed and added for each additional herbicide and target plant combination listed above. Calibration values included in the default data sets were taken from product labels and from published reports such as Reinert and Rodgers (1987).

Further Model Development Efforts and Needs

We anticipate additional needs for improved models for simulation of chemical control of aquatic plants. First, the effort clearly requires more laboratory and semicontrolled field experiments for validation of all processes in simulation procedures. Also required are data regarding critical tissue burdens of herbicides in aquatic plants to effectively predict their responses to herbicide exposure.

Development of more sensitive and accurate measures of plant injury to ascertain degree of mortality, or other measures of effectiveness, following herbicide exposure is another very important need. Finally, incorporation of nonequilibrium modeling capabilities (Cassiday and Rodgers 1988) for other targeted plant and herbicide combinations is required.

Continued development of chemical control simulations will require special understanding of the needs of water resource managers. Data and relationships emerging from projects such as Guntersville Reservoir will be useful in refining predictive techniques. The application of these models for designing improved herbicide application programs is being demonstrated, and we anticipate more intense use of simulations in the future as new formulations and herbicide delivery systems are developed.

References

Cassiday, K. H., and Rodgers, J. H., Jr. 1988. Response of hydrilla (*Hydrilla verticillata* (L.f.) Royle) to diquat and a model of uptake under nonequilibrium conditions. *Environmental Toxicology and Chemistry* 8:133-140.

Clifford, P. A., Rodgers, J. H., Jr., and Stewart, R. M. 1989. Further development of a coupled herbicide fate and target plant species effects model. Pages 274-282 in *Proceedings, 23rd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-89-1. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Clifford, P. A., Rodgers, J. H., Jr., and Stewart, R. M. 1990. Comparison of HERBICIDE simulation results with field measurements. Pages 261-270 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Netherland, M. D. 1990. Herbicide concentration/exposure time relationships: Endothall-hydrilla and Triclopyr-Eurasian watermilfoil. Pages 110-114 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Reinert, K. H., and Rodgers, J. H., Jr. 1987. Fate and persistence of aquatic herbicides. *Reviews of Environmental Contamination and Toxicology* 98:61-98.

Reinert, K. H., Stewart, S., Hinman, M. L., and Leslie, T. J. 1985. Release of endothall from Aquathol granular aquatic herbicide. *Water Research* 19(6):805-808.

Rodgers, J. H., Jr., Clifford, P. A., and Stewart, R. M. 1988. Development of a coupled herbicide fate and target plant species effects model (FATE). Pages 176-183 in *Proceedings, 22nd Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-88-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wooten, J. W., and Stewart, R. M. 1991. See pages 257-265 in this proceedings.

Aquatic Plant Database Development for Lake Marion, South Carolina

by
R. Welch[1] and M. Remillard[1]

Introduction

The Center for Remote Sensing and Mapping Science (CRMS) at the University of Georgia is developing a digital database of aquatic plant spatial distributions for Lake Marion, South Carolina. This work is being sponsored by the US Army Engineer Waterways Experiment Station (WES). The digital database will incorporate plant distribution patterns as delineated from aerial photographs of Lake Marion.

The format of the database will be compatible with the Environmental Systems Research Institute PC ARC/INFO geographic information system (GIS). Access to the database through the PC ARC/INFO GIS will allow calculation of areal statistics of plant distribution patterns, hard-copy production of map products at desired scales, and an easy method for calculating annual changes in plant distribution patterns within the study area.

The database will support evaluation of the white amur stocking effort for aquatic plant management in Lake Marion (Morgan and Killgore 1990) and development of aquatic plant control simulation models as described by Kress, Causey, and Ballard (1990). Welch, Remillard, and Slack (1988) and Remillard and Welch (1991a,b) include example applications of an existing GIS for Lake Marion aquatic plant management activities. Applications described therein include GIS analysis of the areal control effectiveness of aquatic herbicide applications and cartographic modeling techniques for predicting additional colonization sites for aquatic plants in Lake Marion.

This paper provides an overview of methods used to develop the plant distribution database and GIS for upper Lake Marion and presents map products and tabular statistics for the fall 1988 areal distribution of aquatic plant infestations in a section of the Lake Marion study area.

Study Area

Lake Marion, located approximately 56 km southeast of Columbia, SC, was constructed in 1941 by the US Army Corps of Engineers to provide hydroelectric power to the state. The specific study area is confined to upper Lake Marion, which extends approximately 23 km northwest of Interstate Highway 95 and encompasses 17,000 ha (Figure 1). Upper Lake Marion represents a gradual transition from the alluvial floodplain of the Santee River to the impounded lake (Harvey, Pickett, and Bates 1987). Stable water levels and shallow depths (averaging less than 3 meters) create favorable habitat for aquatic plant growth (Patterson and Cooney 1986).

Database Development

Large-scale (1:12,000) color infrared (CIR) aerial photography transparencies were acquired of upper Lake Marion from an aerial photography mission flown on 25 October 1988. Approximately 100 photographic frames were required to cover the study area.

Following acquisition of the CIR transparencies, personnel from the CRMS, the South Carolina Water Resources Commission, and the Santee Cooper Public Service Authority visually surveyed aquatic macrophyte

[1] Center for Remote Sensing and Mapping Sciences, University of Georgia, Athens.

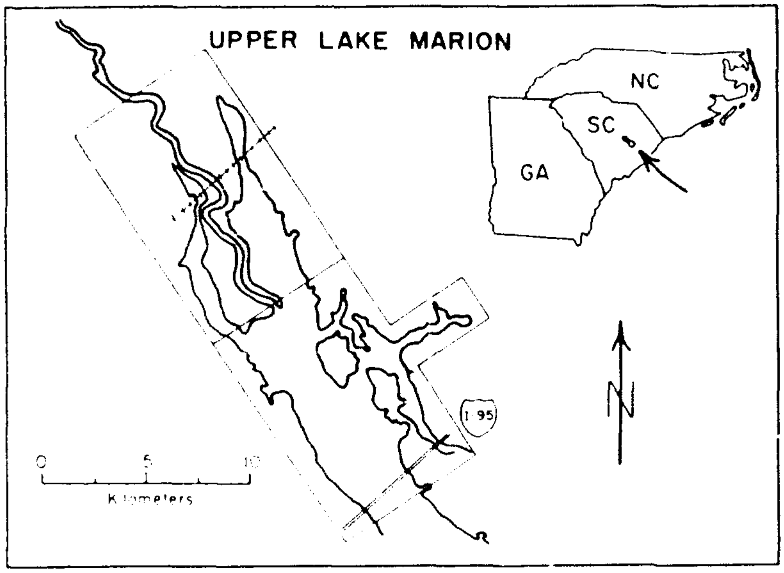


Figure 1. Upper Lake Marion study area

infestations in the study area. During this survey, aquatic plant species were identified; this information was annotated on paper-print copies of the aerial photographs. These ground truth data were then utilized for interpretation of macrophyte species distributions on the remainder of the 1988 CIR transparencies. Outlines of the infestation boundaries of different plant species were then delineated on clear acetate overlays registered to the CIR transparencies.

The plant species boundaries were then digitized directly from the overlays. All digitizing was accomplished with software that automatically corrects for tip and tilt distortions inherent in the aerial photographs and captures vector information (points, lines, and polygons) in Universal Transverse Mercator coordinates. The resulting digital vector files were input to the PC ARC/INFO GIS system. The digital files were then mosaicked and edited, and a relational database was developed which assigned classifications of plant species and plant type (i.e., submergent, emergent, mixed) to the individual polygons in the digital files.

Map compositions depicting species distributions and plant type distributions were then generated for plotting hard-copy map products. Summary areal statistics were generated for individual plant species and plant type classification categories.

Aquatic Plant Distributions

A PC ARC/INFO GIS system for the fall 1988 areal distributions of aquatic plant infestations in the upper Lake Marion study area was developed. Example hard-copy map products and tabular statistics from the GIS system are provided below for a section of the study area located south of Low Falls Landing.

Map products for aquatic plant distributions based on classifications of plant species and plant type are provided as Figures 2 and 3. For areas classified as having mixed plant species or mixed plant types, the classification codes given in Figures 2 and 3 indicate the relative abundance of plant species or type. For example, a polygon classification of "EgHC" in Figure 2 indicates that the lake area delineated by the polygon contained a mixture of *Egeria densa, Hydrilla verticillata,* and *Ceratophyllum demersum*, with *E. densa* the most abundant plant species and *C. demersum* the least abundant plant species.

The GIS was used to calculate areal statistics for plant species and plant types for the section of Lake Marion illustrated in Figures 2 and 3. Table 1 gives areal statistics for plant species. Of the 2,000 ha included in this section of the study area, approximately 349 ha is land, 601 ha is open water, and 1,050 ha is colonized by aquatic plants. Aerial statistics given in Table 1 further indicate that *H. verticillata* is established in approximately 965 ha and that this plant species is the dominant plant in approximately 338 ha.

Table 2 gives areal statistics for plant types in the 2,000-ha section of Lake Marion. Of the 1,050 ha colonized by aquatic plants in the lake area illustrated in Figure 3, emergent

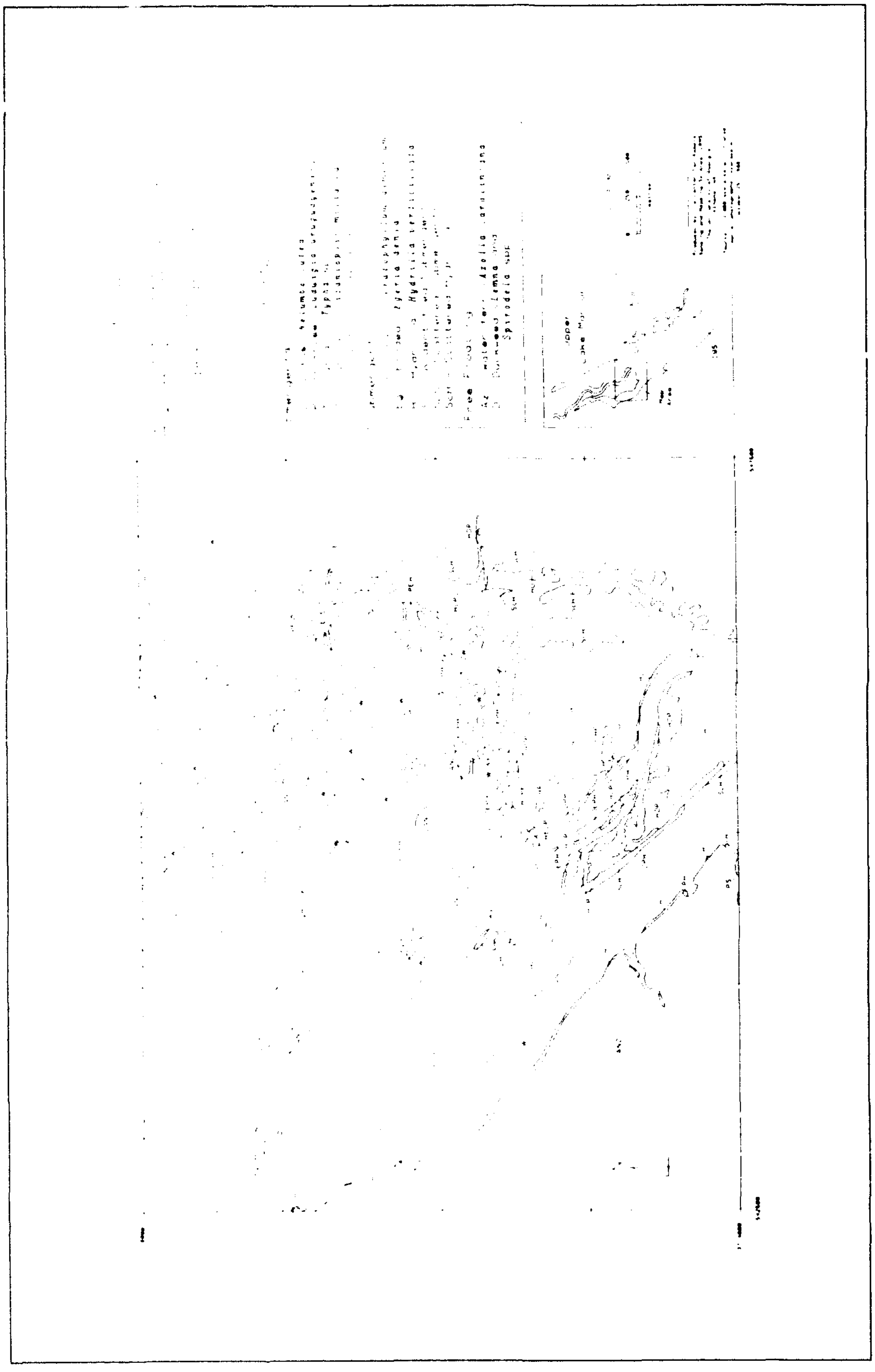


Figure 2. Aquatic plant species distribution map, 1988, for a 2,000-ha section of the upper Lake Marion study area

FFigure 3. Aquatic plant distribution map, 1988, based on plant type for a 2,000-ha section of upper Lake Marion study area

Table 1
Areal Extent of Aquatic Macrophyte Species in a 2,000-ha Area of Upper Lake Marion

Species[1]	Hectares	Acres
Land	349.366	863.057
OW[2]	601.086	1,484.896
OWD[3]	7.495	18.515
D	2.383	5.886
DEPH	23.775	58.733
DES	13.892	34.319
DH	0.981	2.422
DPH	22.245	54.954
EDPH	132.337	326.921
EPH	11.669	28.826
EgCHD	15.073	37.235
EgCHPD	4.467	11.036
EgHC	236.659	584.632
EgHCPDE	126.474	312.435
H	172.452	426.018
HD	21.746	53.719
HDP	23.590	58.277
HDPAz	58.324	144.082
HDPE	35.914	88.721
HEDP	1.433	3.539
HP	19.369	47.848
L	0.493	1.218
LH	0.512	1.265
LPEH	2.168	5.357
PEDS	18.014	44.500
PH	1.012	2.499
PS	0.292	0.720
S	8.802	21.743
SE	0.699	1.728
SEP	20.969	51.800
ScH	55.396	136.847
ScS	5.498	13.581
ZT	5.417	13.383
Total	2,000.000	4,940.711

[1] See Figure 2 legend for definition of plant species codes.
[2] Open-water areas.
[3] Open-water areas with minor duckweed infestations.

Table 2
Areal Extent of Aquatic Macrophyte Types In a 2,000-ha Area of Upper Lake Marion

Type	Hectares	Acres
Land	349.366	863.057
Open water	601.086	1,484.896
Emergent	15.788	39.002
Emergent/submergent[1]	226.897	560.516
Submergent	417.912	1,032.392
Submergent/emergent[2]	328.058	810.420
Scattered submergent	60.893	150.428
Total	2,000.000	4,940.711

1 Areas with a mixture of emergent and submergent plant types, with emergent types being most abundant.
2 Areas with a mixture of emergent and submergent plant types, with submergent types being most abundant.

plant species dominate approximately 343 ha, and submergent plant species dominate approximately 807 ha.

Additional Database Development Efforts and Applications

During fiscal year 1991, aquatic plant distributions delineated from aerial photographs of the study area taken during fall 1990 will be added to the database. The Lake Marion GIS will be used to determine areal statistics for plant species and plant types, as described above for 1988 aquatic plant distributions. Additionally, the GIS will be used to calculate changes in areal distributions of plant species and types between 1988 and 1990.

This information will be used to evaluate the effectiveness of the ongoing white amur stocking effort described by Morgan and Killgore (1990). Further, the database will be updated at least every 2 years through 1994, and additional information will be generated by the GIS for evaluation of the white amur stocking effort. Additionally, changes in areal distributions of aquatic plants in the study area through time which can be attributed to impacts from white amur stocking efforts will be used as a basis for analyzing results from the WES White Amur Stocking Rate Model (Boyd and Stewart 1991).

References

Boyd, William A., and Stewart, R. Michael. 1991. See pp 266-278 in this proceedings.

Harvey, R. M., Pickett, J. R., and Bates, R. D. 1987. Environmental factors controlling the growth and distribution of submersed aquatic macrophytes in two South Carolina reservoirs. *Proceedings, Sixth North American Lakes Management Society Meeting*. Portland, OR.

Kress, M. R., Causey, E. M., and Ballard, J. R., Jr. 1990. Digital database to support aquatic plant control modeling. Pages 271-282 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Morgan, Raymond P., II, and Killgore, K. J. 1990. Evaluation of triploid grass carp introduction in Lake Marion, South Carolina: Fisheries investigations. Pages 212-223 in *Proceedings, 24th Annual Meeting, Aquatic Plant Control Research Program.* Miscellaneous Paper A-90-3. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Patterson, G. G., and Cooney, T. W. 1986. Sediment transport and deposition in Lakes Marion and Moultrie, South Carolina. Pages 1336-1345 in *Proceedings, Third International Symposium on River Sedimentation.* The University of Mississippi, University, MS.

Remillard, M., and Welch, R. 1991a. GIS technologies for aquatic macrophyte studies; I. Database development and changes in the aquatic environment. *Landscape Ecology* (in press).

Remillard, M., and Welch, R. 1991b. GIS technologies for aquatic macrophyte studies; II. Modeling applications. *Landscape Ecology* (in press).

Welch, R., Remillard, M., and Slack, R. 1988. Remote sensing and geographic information system techniques for aquatic resource evaluation. *Photogrammetric Engineering and Remote Sensing* 54(2):177-185.

Simulation Needs for the Future

by
H. W. West,[1] *R. M. Stewart,*[1] *and M. R. Kress*[1]

Introduction

The Aquatic Plant Control Research Program (APCRP) initiated research work related to aquatic plant control (APC) simulation modeling in the early 1980's, as discussed in the overview paper.[2] This research was structured in such a manner to allow for systematic evaluations of existing and prototype mechanical control techniques and available biological control agents under simulated operational conditions.

The basic philosophy in developing these first-generation simulation procedures/ concepts was to "model" the control method as an entity that would allow for simulations of the interactions of the method (such as a *mechanical harvester* or a white amur fish) with the in situ plants as they occur in the water body. The basic understanding of this modeling scenario was that the "effectiveness" of any proposed control method would be highly dependent upon the diversity and structure of the in situ aquatic plant community and its water body configuration (geometry, water depths, and other special features or characteristics).

As we look to the future, especially for the next decade or so, what should the role of APC computer simulations be or focus on?

With both software and hardware changing rapidly, what directions should we (i.e., the research community) take to provide the best capability for the field users. To help with this open forum, a panel of five key individuals was selected as follows:

Dr. Ted Center, US Department of Agriculture.

Dr. Rose Kress, US Army Engineer Waterways Experiment Station (WES).

Mr. Leon Baker, Tennessee Valley Authority.

Dr. John Rodgers, University of Mississippi.

Mr. Mike Stewart, WES

Future Research Areas

The forum session on Simulation Needs for the Future was initiated with a presentation by Mr. West, which focused on four research areas: state-of-the-art simulation software; integrated research and development (R&D) activities; hardware platforms, operating systems, and networks; and comprehensive information bases. Each of these is discussed briefly below.

State-of-the-art simulation software

Development work is needed to allow for simulation of the effects of multiple-plant species environments; evaluation of multiple treatment applications for chemical control methods, and the effectiveness of multiple treatment methods; and modeling of ecosystem effects such as water body water quality conditions (dissolved oxygen, pH, etc.).

Simulation capabilities are also needed for new control methods as they become operational. These include herbicides based on

[1] US Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] R. Michael Stewart. 1991. See pp 251-256 in this proceedings.

new active ingredients, as well as those based on new formulations of existing active ingredients, and insect and pathogenic agents soon to become operational. The ones that should be addressed by the APCRP in the near term are listed in Figure 1.

With the recent advancements in specialized tailored software, improvements are needed to existing simulation software in terms of user interface capabilities, namely menu structures, help features, and color graphics. Also, with the advancements in geographic information systems (GIS) and data base management systems (DBMS), it is necessary that these capabilities be interfaced/integrated with the PC-based APC simulation software packages.

Within any analytical simulation model, the output products can be very detailed, and in many cases not very conducive to quick understanding of the results. Therefore, it is necessary that simulations and special-purpose output graphics be developed for improved visualization of APC simulations and parameter interactions.

Integrated R&D activities

As part of the APCRP, basic information and relationships on control agents and their interactions with the target plant, and with the environment as a whole, are developed under the respective control technology research areas during the development of operational control techniques for the control agents. This information is used in developing the first-generation APC simulation models.

Once developed, the APC simulation models allow systematic evaluation of the validity of these relationships, which in turn provides new insights and emphasis for conducting additional laboratory and field research studies of the control agent or technique. For example, the *Neochetina* and waterhyacinth simulation model (INSECT) results are providing useful insights for needed research on seasonal shifts in *Neochetina* reproductive capacity.

As stated above, the capabilities provided by APC simulation models, in terms of systematic evaluation of existing relationships for aquatic plants and their control agents, is a new role for simulation technology in the 1990's. This feedback between modeling and the development of parameter relationships (shown in Figure 2) should provide for a better overall understanding of the interactions between the in situ control agent and the host plant. This information in turn may lead to more effective aquatic plant management capabilities and strategies.

Hardware platforms, operating systems, and networks

The PC-based platforms/systems currently under development will have capabilities that will provide for improved understanding of simulation results, thereby broadening our knowledge of aquatic plant control operations and activities. Some of the most improved aspects/features that we plan to incorporate into these PC-based systems are:

- Multitasking/multiuser capabilities.
- Windowing.
- Networking.
- Read/write optical disk devices.
- Color graphics devices (screen copiers).
- Color plotters.

One of the most important features to be included in our improved PC-based systems is "windowing." This new technology is changing the way we can access and visually display information. Windowing will provide the following features:

- Different computers can access the same display device.
- Multiple-application software can be run on the same display device.

CHEMICALS

NEW FORMULATIONS OF EXISTING HERBICIDES

BENSULFURON METHYL
FLURPRIMIDOL
PACLOBUTRAZOL
UNICONAZOL
— PLANT GROWTH REGULATORS WITH VARYING SPECIFICITY

INSECTS

BAGOUS AFFINIS
BAGOUS n. sp.
HYDRELLIA PAKISTANAE
HYDRELLIA n. sp.
— HYDRILLA

NAMANGANA PECTINCORNIS
NEOHYDRONOMUS AFFINIS
— WATERLETTUCE

PATHOGENS

MYCOLEPTODISCUS TERRESTRIS – WATERMILFOIL
MACROPHOMINA PHASEOLINA – HYDRILLA

Figure 1. Near-future control method simulations

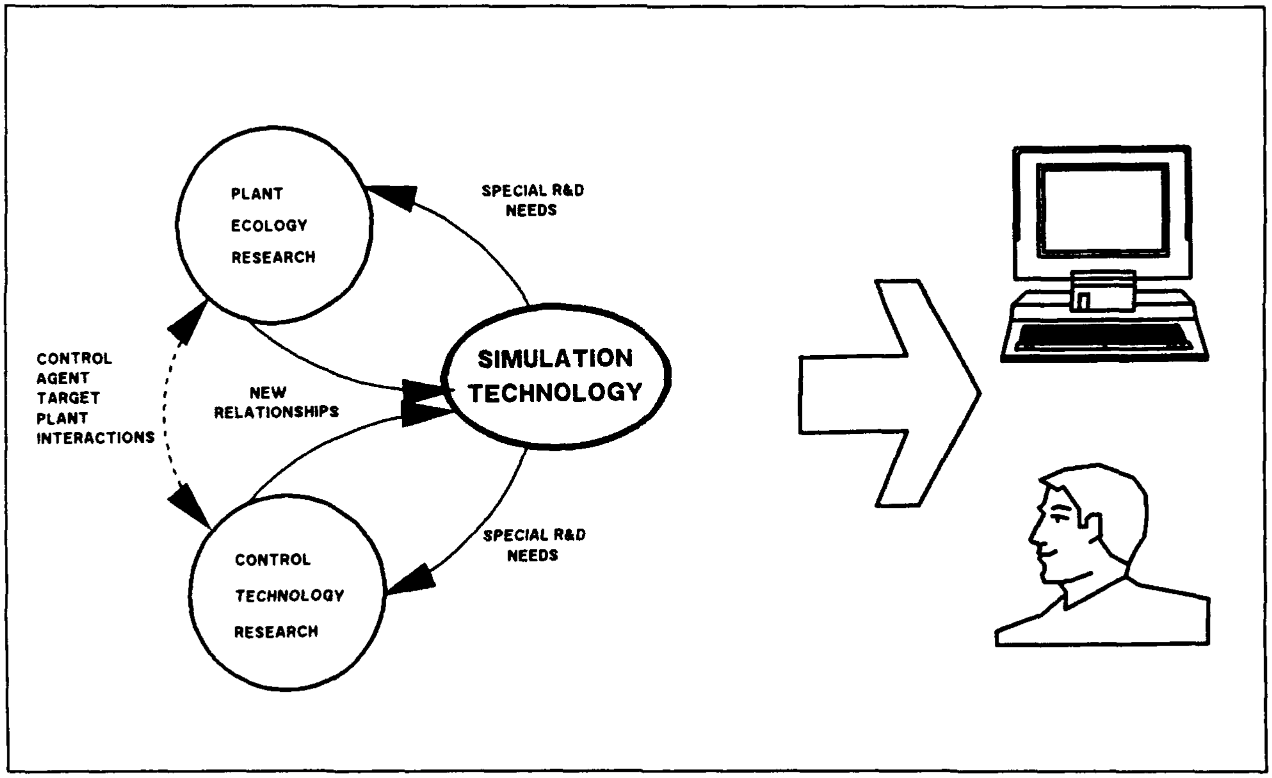


Figure 2. Integrated R&D tasks, resulting in enhanced simulation capability and improved control techniques and management

- Both text and graphical information can be displayed at the same time.

- Different computers can share the same information base.

Figure 3 illustrates a platform that is displaying narrative, geographical (map), and image data.

As we move into the next decade, computer technology will allow for improved methods for information display. The PC-based windowing and color capability will add a new dimension in information understanding and will thereby improve information exchange to allow for better APC management opportunities. APC simulation technology will benefit significantly with the advancement in hardware, operating systems, and networks. Our models will be restructured/modified/improved/integrated to provide for an advanced APC simulation capability.

Comprehensive information bases

The recent advancement in GIS and DBMS software, and the interface of these capabilities with automated data update capabilities such as generated by satellite and aircraft, will allow for the development of more comprehensive information bases for water bodies with aquatic plant infestations. Satellite imagery and positional information from the network of global positioning satellites and

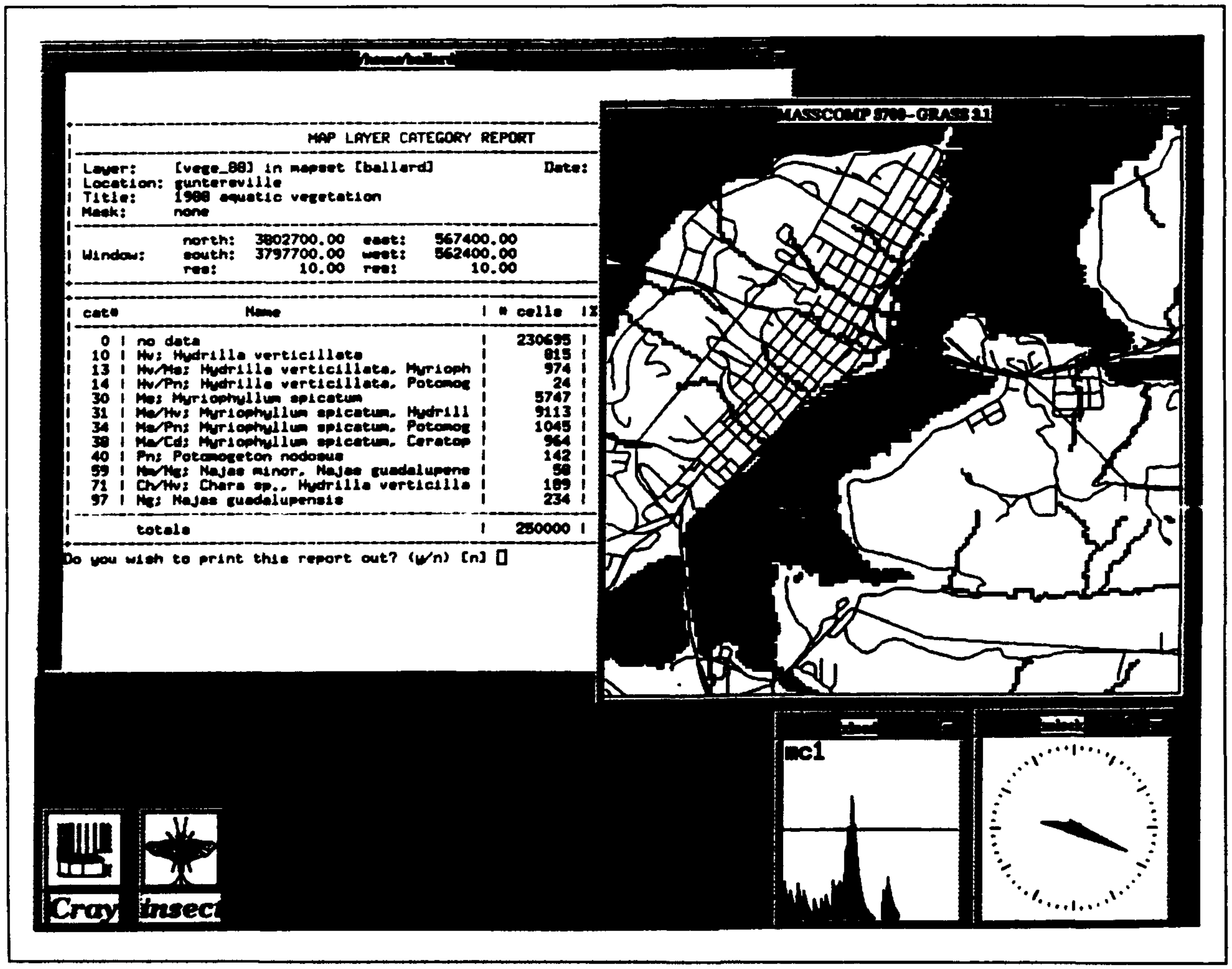


Figure 3. Windowing capability

special-purpose analysis software provide for near real-time updates of the databases of aquatic plant infestations.

Information bases are needed at the regional, water body, and site-specific levels (Figure 4) to more effectively serve the APCRP and to provide users of the developing software with the necessary input data for their regional area of interest. Emphasis during the next few years will be to develop an improved technical information base for the APCRP, the components of which are shown in Figure 5.

The new software and hardware capabilities will be interfaced with the APC simulation software packages to allow for more timely and realistic APC simulation results.

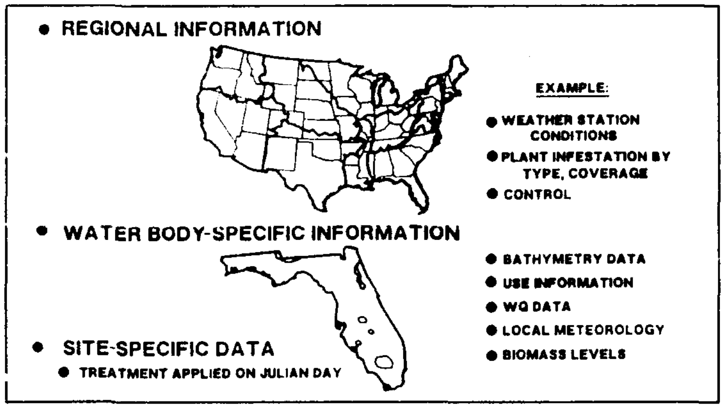
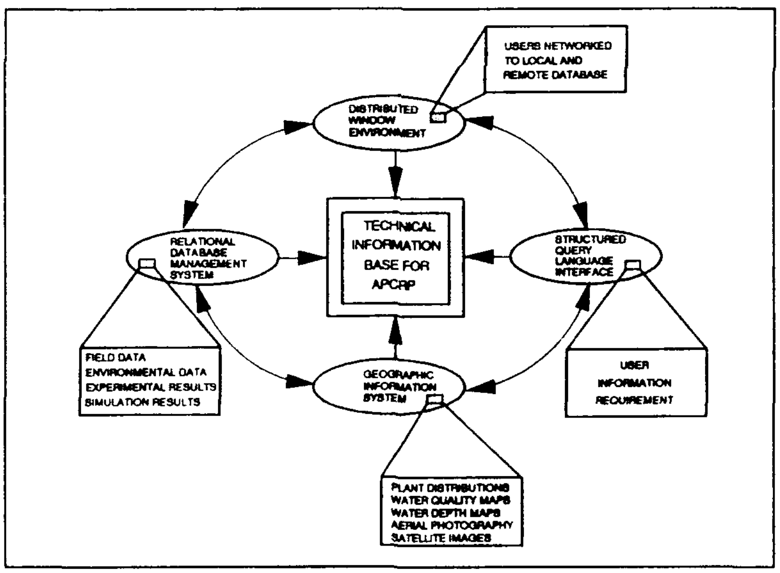


Figure 4. Levels of information bases

Discussion and Panel Comments

Questions and comments from individuals from the floor were responded to by the panel, and their questions and comments were recorded.



Figures 5. Components of improved technical information base for the APCRP

Annual Report - Aquatic Plant Control Operations Support Center

by
William C. Zattau[1]

In October 1980, the Jacksonville District was designated by OCE as the APCOSC in recognition of the District's knowledge and expertise gained through the administration of the largest and most diverse aquatic plant management program in the Corps. The APCOSC personnel assist other Corps elements and other Federal and State agencies in the planning and operational phases of aquatic plant control. The specific duties, relationships with other Corps APC programs, and guidelines for utilization of the APCOSC are outlined in ER 1130-2-412.

The Center responded to 141 requests for assistance during FY 1990. A breakdown of these activities appears in Table 1. Figure 1 indicates the types of information requested; Figure 2 provides a breakdown as to source of information requests.

Table 1
APCOSC Contacts, FY 90

Type Assistance	Corps				Other Federal	Other Country	State/ Local	Industry	Private	Total
	OCE	WES	Division	District						
Planning	1	3	5	22	3	0	3	1	0	38
Operations	3	3	3	17	3	1	11	9	2	52
Research	2	16	1	4	1	0	4	5	1	34
Training	0	1	0	11	0	0	4	1	0	17
Total	6	23	9	54	7	1	22	16	3	141

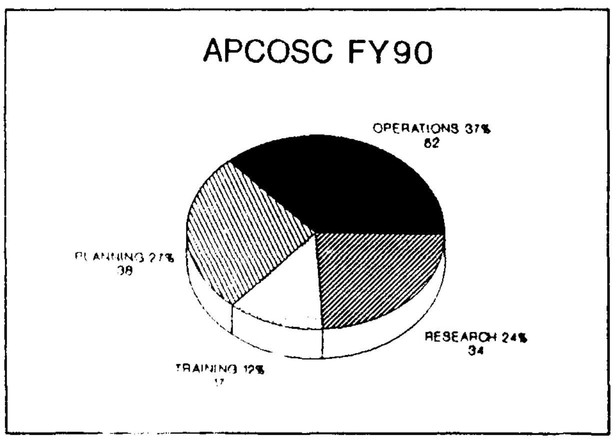


Figure 1. Types of information requested

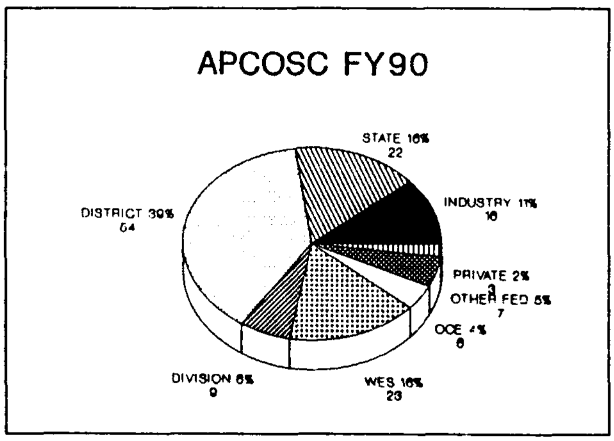


Figure 2. Information request sources

---

[1] US ArmyEngineer District, Jacksonville; Jacksonville, FL.

The demand for and type of services performed by the Center vary from year to year, based on the type of problems encountered by Corps elements or other agencies. Four basic types of information are requested: planning, operations, research, and training. Planning assistance includes determinations of water body eligibility and allowable costs, computation for benefit-cost ratios, methods of data acquisition, and other factors that enter into the process of planning an Aquatic Plant Control Program. Operations assistance involves most aspects of chemical, mechanical, biological, and integrated technology. The Center provides data, information, and recommendations relating to operational activities. Information on research activities is provided to requestors if available, or the requests are referred to the WES. Training assistance includes providing materials for use in educational and training programs, and conduct of the Pesticide Applicators Training Course and the Aquatic Plant Management Course by Center staff.

During fiscal year 1990, the Center published the Information Exchange Bulletin and the APCOSC Annual District/Division Survey (for fiscal year 1989 treatments). The Pesticide Course was provided at the request of Mobile District. As a result of a new Memorandum of Agreement, the Pesticide Course was also given to the Seminole Tribe of Florida. A new 1.5-day Aquatic Plant Management Course was provided for the Galveston, St. Paul, and Nashville Districts. The new course provides an overview of the Program as well as outlines of the various management technologies.

The APC Program Evaluation Guidance Task Force held three meetings. The Task Force was chartered to "develop a self-evaluation system for Corps aquatic plant managers" and "to assess the efficiency and effectiveness of the programs, and to ensure the wise use of Federal funds." Jim Wolcott (CECW-ON) serves as Project Coordinator, and Bill Zattau (CESAJ-CO-OR-A) serves as the Task Force Team Leader. Task Force members include Vicki Dixon (CESWD-CO-RR), Lewis Decell (CEWES-EP-L), Joe Kight (CESAM-FO-LS), Bob Rawson (CENPS-OP-PO), and Maurice Simpson (CEORN-OR-R). At this time, the draft document includes a detailed overview of the Program, charts depicting various District programs, and checklists of Program responsibilities at the project, District, Division, and CECW-ON levels.

Synopsis of the District/Division Aquatic Plant Management Operations Working Session

by
William C. Zattau[1]

The annual Working Session was held 27 November 1990 during the Aquatic Plant Control Research Program Review. Representatives from Headquarters, five Division offices and 13 Districts attended, as did local cooperators from five states. The session was chaired by the Aquatic Plant Control Operations Support Center.

During the meeting, a review was conducted on results of suggestions made during last year's session. The results are as follows:

- **APCRP work unit updates**: Operations personnel requested more periodic updates. I discussed the idea with the APCRP Program Manager, who was receptive to the idea pending more discussion. Possible timing for publication of these fact sheet-type updates would be May.

- **APCOSC Electronic Bulletin Board**: The essential legwork has been completed by the APCOSC. Concern exists regarding user-friendliness and volume of use. If a user-friendly system can be provided, and an appropriate amount of use is forecast, a system will be tested during FY 91. In early 1991, the APCOSC will distribute a survey to probable users in order to estimate usage.

- **APC Program Evaluation Guidance Task Force**: The formation and charter of the Task Force was addressed last year. Subsequently, three Task Force meetings were held, and the resulting draft document has been forwarded to CECW-ON for review and comment.

- **Increased publication of field manuals or field guides**: Limited discussion on the publication of field manuals or guides resulted.

Before this year's session, the APCOSC distributed a memorandum to POCs for Districts with cost-shared APC programs requesting response to suggested discussion topics. POC responses were consolidated and distributed prior to the session.

The four proposed topics were brought up for discussion at the Working Session. Initially, discussion centered around the concept of the Federal interest in cost-shared aquatic plant management operations. The major comment was that the concept needed better definition. Related discussion addressed water body eligibility requirements, the definition of navigable water as applied to the program, and prioritization of operations during budget shortfalls.

In regard to program management and budget prioritization, a suggestion was made to provide a mechanism or procedure, perhaps through a budget matrix, which would ensure program-wide management and budgetary (or cost/acre) consistency. Also discussed was the need to provide Headquarters with an improved method of evaluating operations in District cost-shared programs. This dialogue prompted an explanation of the budget process. The need and importance for proper justifications was stressed.

---

[1] US Army Engineer District, Jacksonville; Jacksonville, FL.

The status of ER 1130-2-412 was addressed. An update is essentially complete, but acceptance is contingent upon approval of revised Local Cooperation Agreement language by the LCA Committee. Requested modifications have been made and returned to the Committee.

The current format of the APCOSC Annual District/Division Survey was discussed. Participants agreed that, while it contained excellent information, the survey would be of more value if the data provided by the Districts were calculated in a consistent manner. The Center agreed to provide more guidance when requesting data for the FY 90 survey. It was suggested that a simplified database system be developed as a reporting procedure.

The session closed with a brief discussion by state cooperators of their funding situations. Cooperators reported varying degrees of funding problems.

Working session participants felt that the existing PEG Task force, or similar group, could address or clarify the concepts of Federal interest, program eligibility requirements, navigability, budget prioritization, and justification.

Vermont Aquatic Plant Control Program

by
Joseph J. Debler[1]

The US Army Engineer District, New York, and the State of Vermont completed the ninth year of a cooperative program for the control of nuisance species of aquatic plants on Lake Champlain. The major species of concern to date have been Eurasian watermilfoil (*Myriophyllum spicatum*) and waterchestnut (*Trapa natans*).

As reported last year, Eurasian watermilfoil was not harvested because no proposals for harvesting were submitted to the State. The 1990 program was therefore confined to the harvesting of waterchestnut from southern Lake Champlain, as well as two new small areas (Dead Creek and Upper East Creek), both of which drain into Lake Champlain. The purpose of this harvesting was to prevent the further northward spread of this plant in the lake and to prevent expansion from the new areas.

Approximately 150 acres of waterchestnut were harvested, using a combination of deep-water harvesters, a high-speed transport barge, and hand-pulling crews operating from a boat. Harvesting took place between 1 August and 21 September 1990.

Mechanical harvesting is considered to be very effective in controlling the northward spread of waterchestnut in Lake Champlain. However, the harvesting must be done each year to prevent reinfestation.

The only problem arose when the State expressed concerns in signing the certificate of authority in the Local Cooperation Agreement (LCA). Adding a paragraph to the LCA that absolved the State of obligating future legislative appropriations solved the problem.

Proposals to add Lake Bomoseen and certain biocontrol measures for Eurasian watermilfoil are still under consideration.

[1] US Army Engineer District, New York; New York, NY.